JOURNAL of the AMERICAN SOCIETY *of* *NAVAL ENGINEERS* Inc.

November, 1956

Volume 68 Number 4

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of

The American Society of Naval Engineers, Inc.

PUBLISHED QUARTERLY

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SIXTY-EIGHTH YEAR

VOL. 68 NOVEMBER, 1956 NO. 4

Published Quarterly at Washington, D.C., by The American Society of Naval Engineers, Inc.

Entered as Second Class Matter at the Post Office at Washington, D.C., and at Nashville, Tenn. Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 3, 1918.

Subscription Rates for Non-Members

The subscription price of the JOURNAL, postpaid to points in the United States and possessions is $9.00. Single copies, $2.25. To other countries, $20.00. Single copies, $5.00. All subscriptions payable in advance.

Make checks, drafts and postal money orders payable to THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

Advertising rates will be furnished on application.

Addresses will be changed at any time, but only upon notification. Immediate notice should be given of any delay in the receipt of the JOURNAL.

Address all communications for the Society to

THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

Suite 1004, Continental Building
1012 14th Street, N.W.
Washington 5, D.C.

The American Society of Naval Engineers, Inc., has no official connection with the Navy Department.

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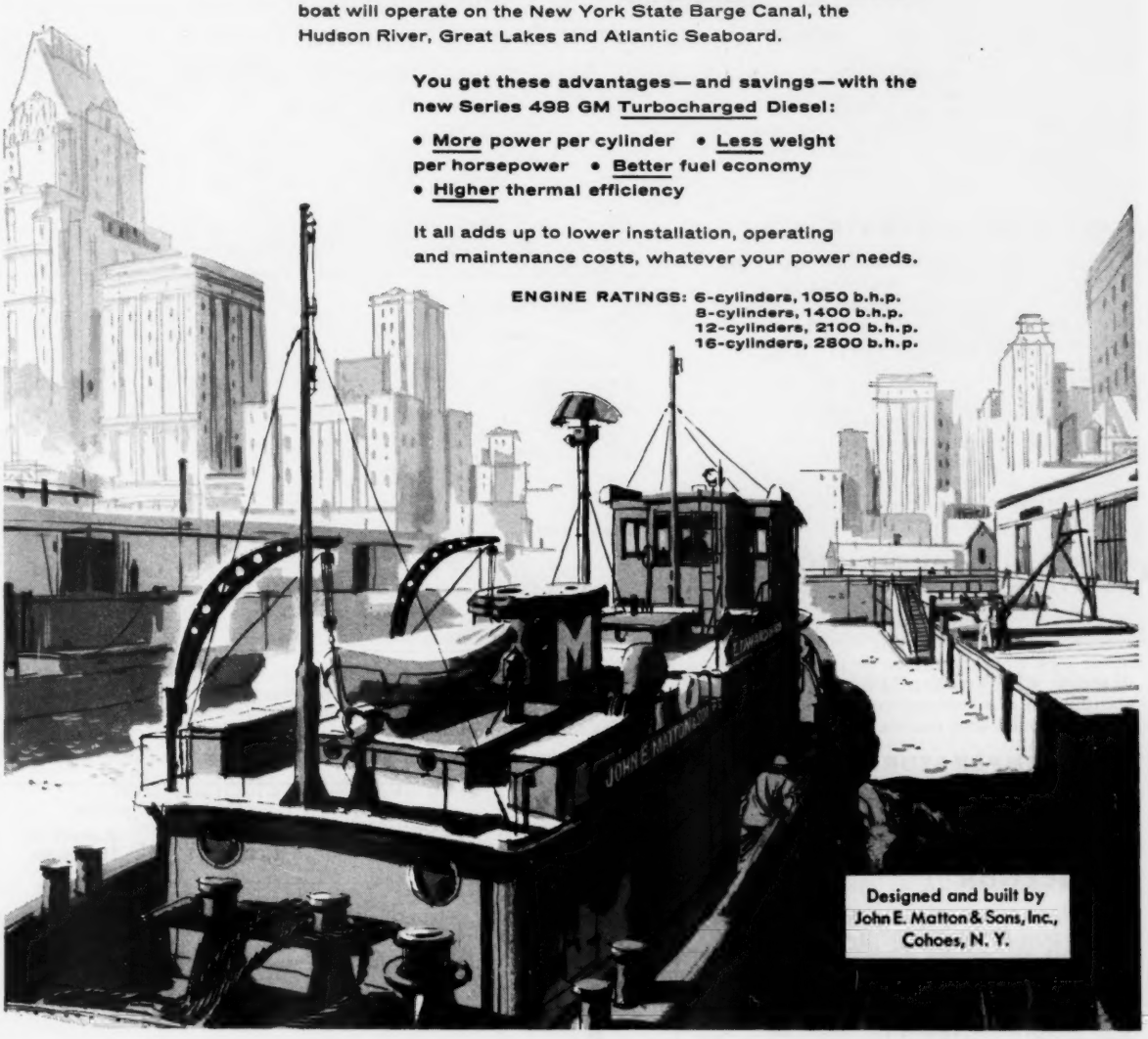

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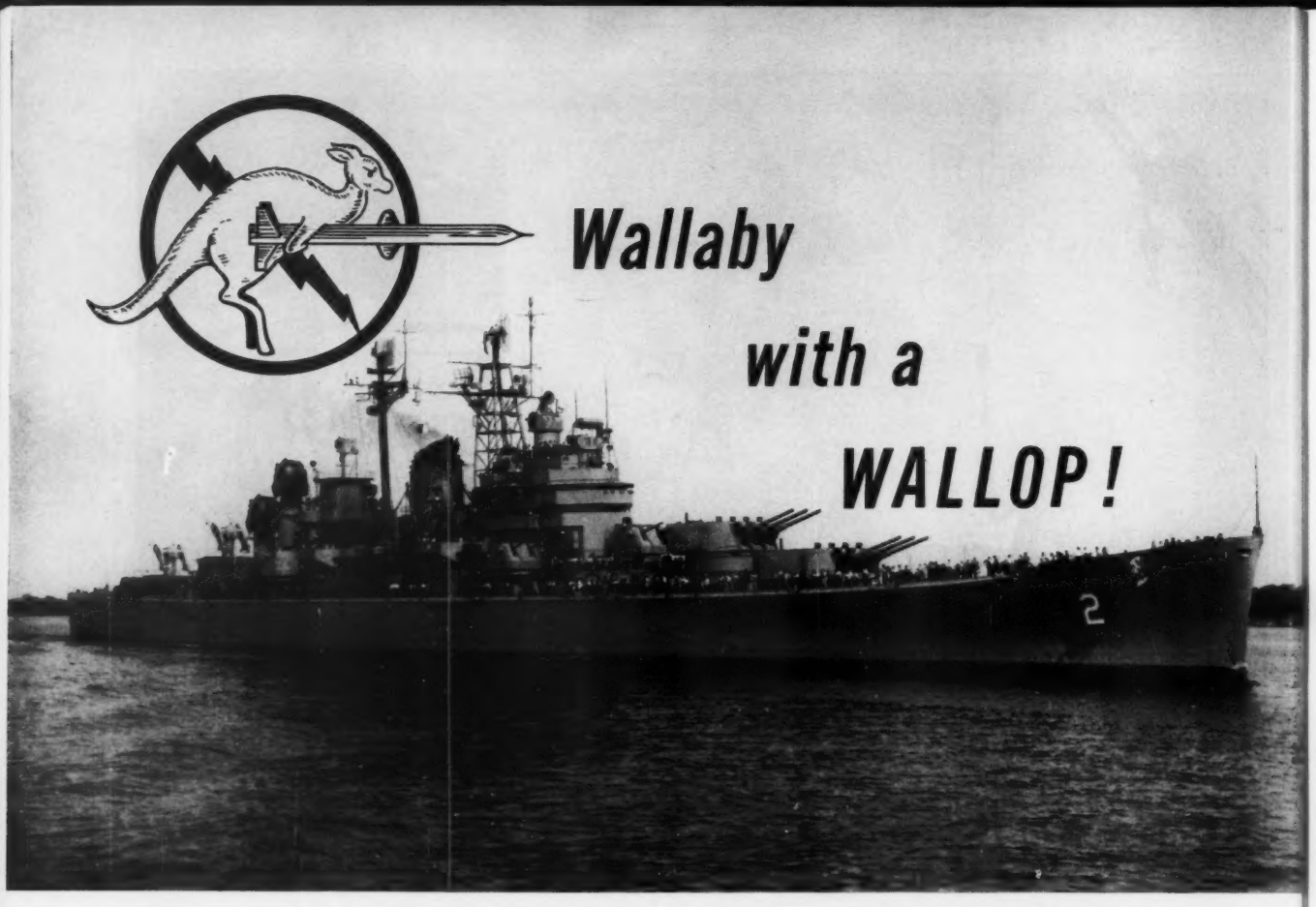

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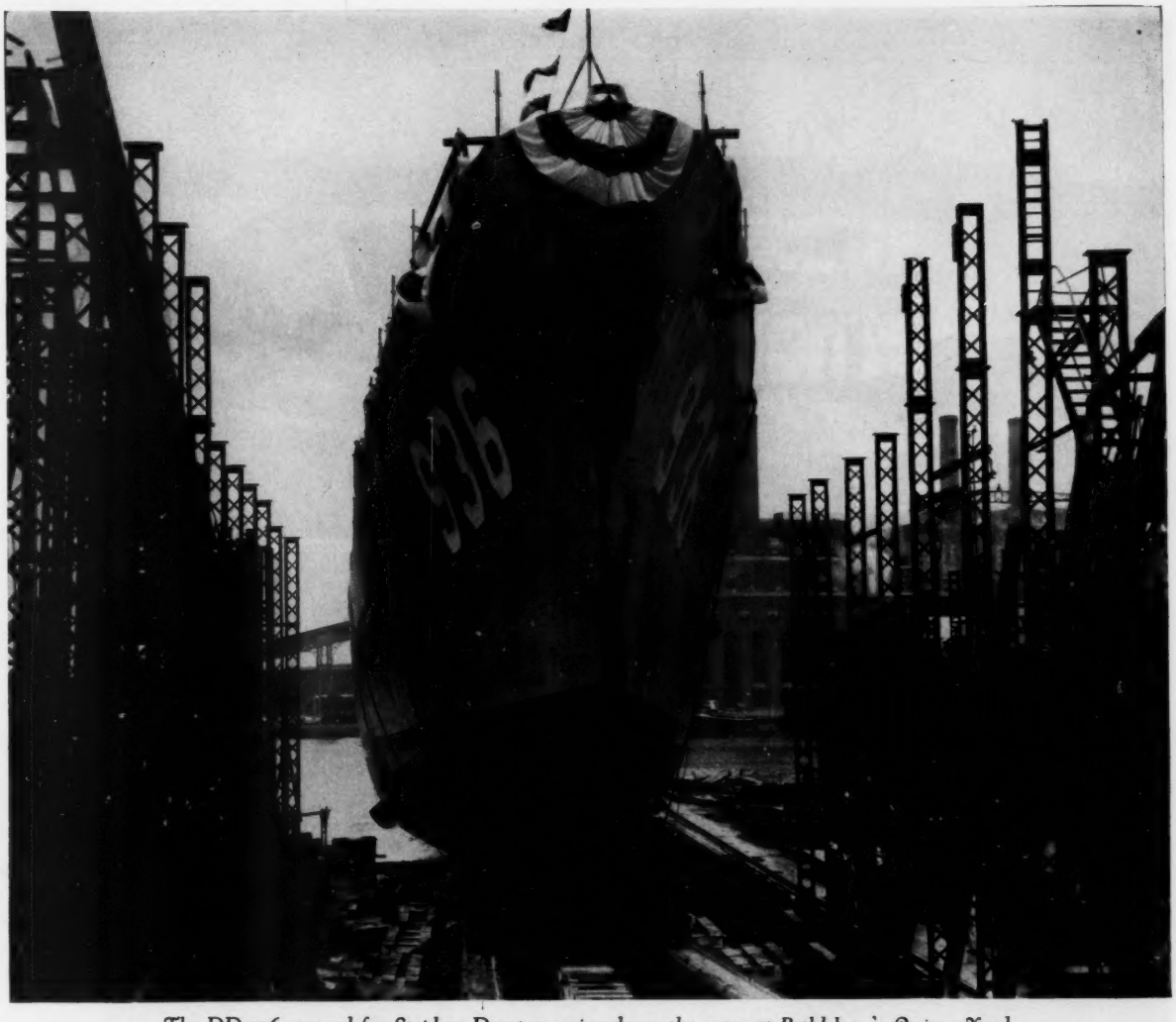

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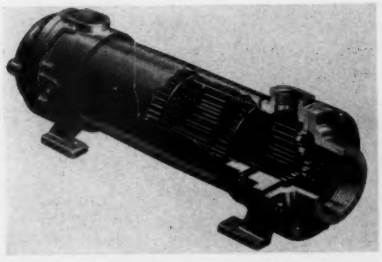

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His name is Michael J. Quinlan and he's a ships pilot. He has never been outside the United States but he knows more about international trade than most people. For the past 27 years, Mr. Quinlan has piloted more thousands of tons of cargo, in and out of harbors, in more ships than he'd care to count.

Tungsten, tin, rubber, coffee are just a few of the items that he knows we don't produce in this country and must import to better and protect—our way of life.

Mr. Quinlan is an American close to the situation. He remembers the lack of American Ships when World War II broke out—the superhuman effort American factories, shipyards and seamen made to save the situation.

He knows that many of our imports and exports are now being shipped in foreign bottoms. He feels that if an emergency should come again, we would be in trouble—until we could reactivate and build shipyards, train people to build ships, train men to man them. He knows the one thing we can't do is train an enemy to wait, while we get busy closing the gap . . . and that gap, right now, is widening.

America can't afford "holidays" from shipbuilding. Mr. Quinlan hopes we plan to do something about it.

M-378

The Babcock & Wilcox Company, which has helped to power so many thousands of American ships, is continuing to work in the tradition of engineering excellence which has made the U. S. A. an acknowledged leader in the design and construction of merchant and naval vessels.

BABCOCK & WILCOX

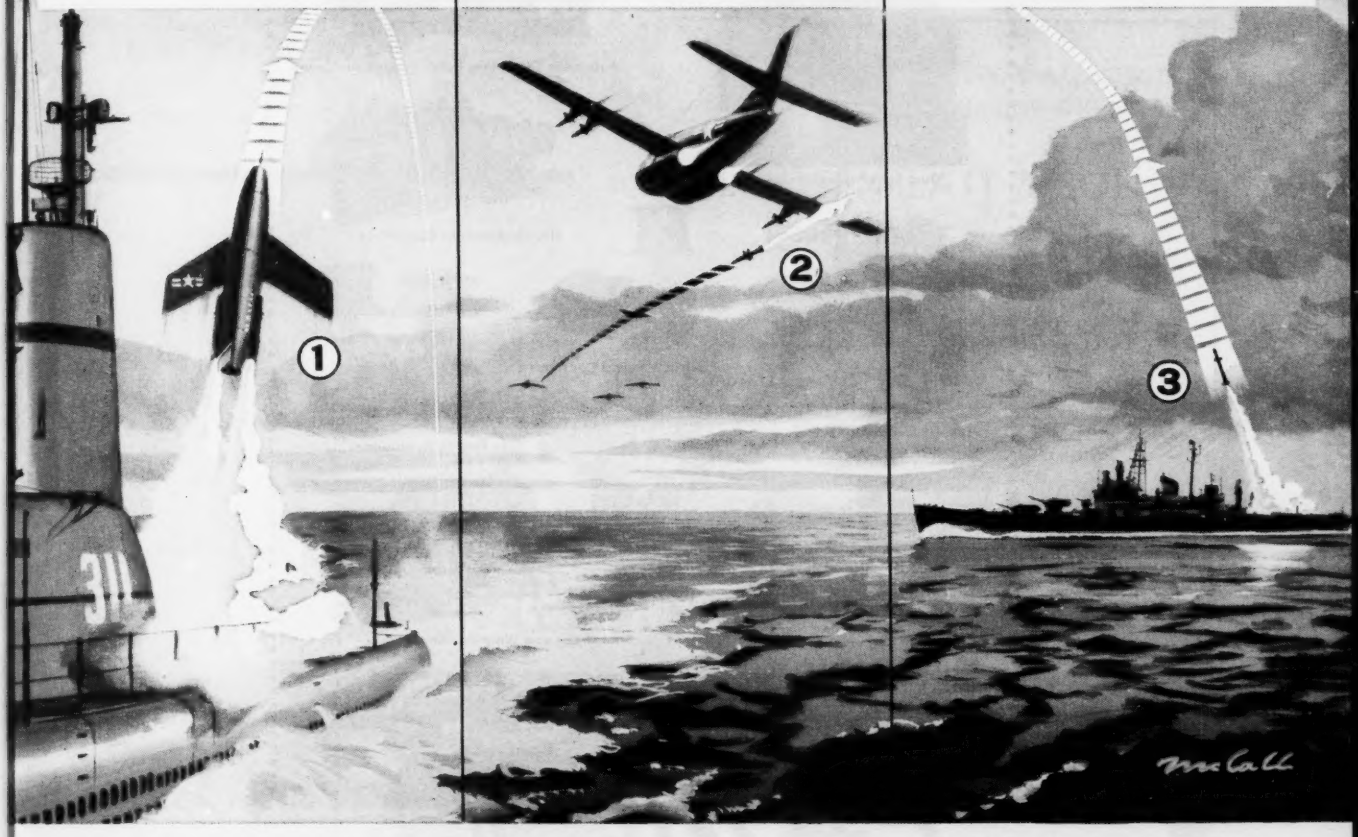
BOILER DIVISION

THE BABCOCK & WILCOX COMPANY, BOILER DIVISION, 161 East 42nd St., New York 17, N. Y.

1. SURFACE-TO-SURFACE missile—Chance Vought's Regulus—can be launched from ship or submarine to destroy distant shore target. A Sperry stabilization system provides the electronic brain which holds Regulus on its course with a vise-like grip.

2. AIR-TO-AIR missile—Sperry Sparrow I—gives carrier-based interceptors deadly weapon against enemy jets. Developed by Sperry for the Bureau of Aeronautics, Sparrow I, a rocket-powered, supersonic weapon, is in production for fleet use.

3. SURFACE-TO-AIR missile—Convair's Terrier—travels a precise radar beam to destroy enemy aircraft. Produced for the Bureau of Ordnance, Sperry designed and built radars are used to control Terrier's flight and to make possible the deadly accuracy of this missile.



NEW NAVY MIGHT EMPLOYS MISSILES OF ALL TYPES

The U. S. Navy has come a long way from the world's first missile, shown at right, to the missiles employed in the fleet today. Our modern Navy, with its modern weapons, has new tactical power to strengthen our nation's defenses. Sperry, too, has come a long way since its pioneering work in gyroscopics and missiles. Today Sperry is putting its many capabilities to work in seven major missile systems—of all types—ranging from complete systems' cognizance to major sub-system responsibility.

In 1916 Sperry produced the first guided missile, a pilotless aerial torpedo for the Navy.

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Great Neck, New York
DIVISION OF SPERRY RAND CORPORATION

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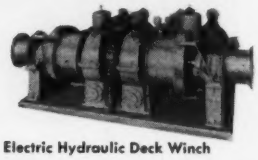
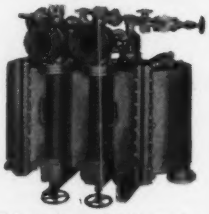
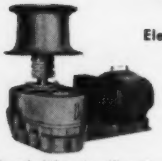
Automatic Tensioning Hoist — Airplane Crane



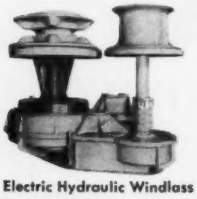
Electric Hydraulic Deck Winch



Tubejet Steam Jet Air Ejector

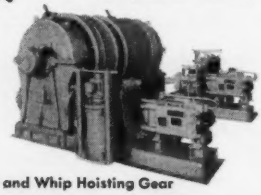


Electric Warping Capstan

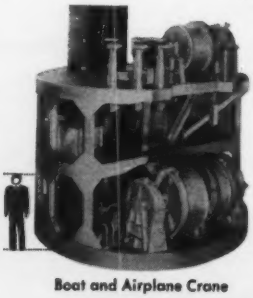


Electric Hydraulic Windlass

Warping Winch



Boat Crane and Whip Hoisting Gear



Boat and Airplane Crane

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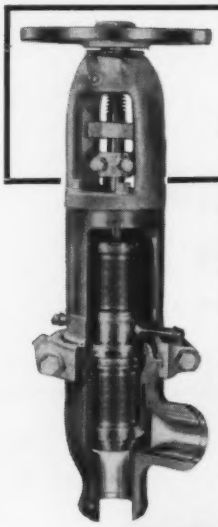

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This is the type of valve found in the engine rooms of the *Nautilus* and the *Seawolf*, and in Navy's plans for added atomic-powered construction. The valve design and application are new, but the brand is well known for dependability.

From the start of nuclear power development, Crane was ready for the problems of controlling radioactive fluids. Crane had the skill in valve metallurgy and engineering. Crane had the background in quality production.

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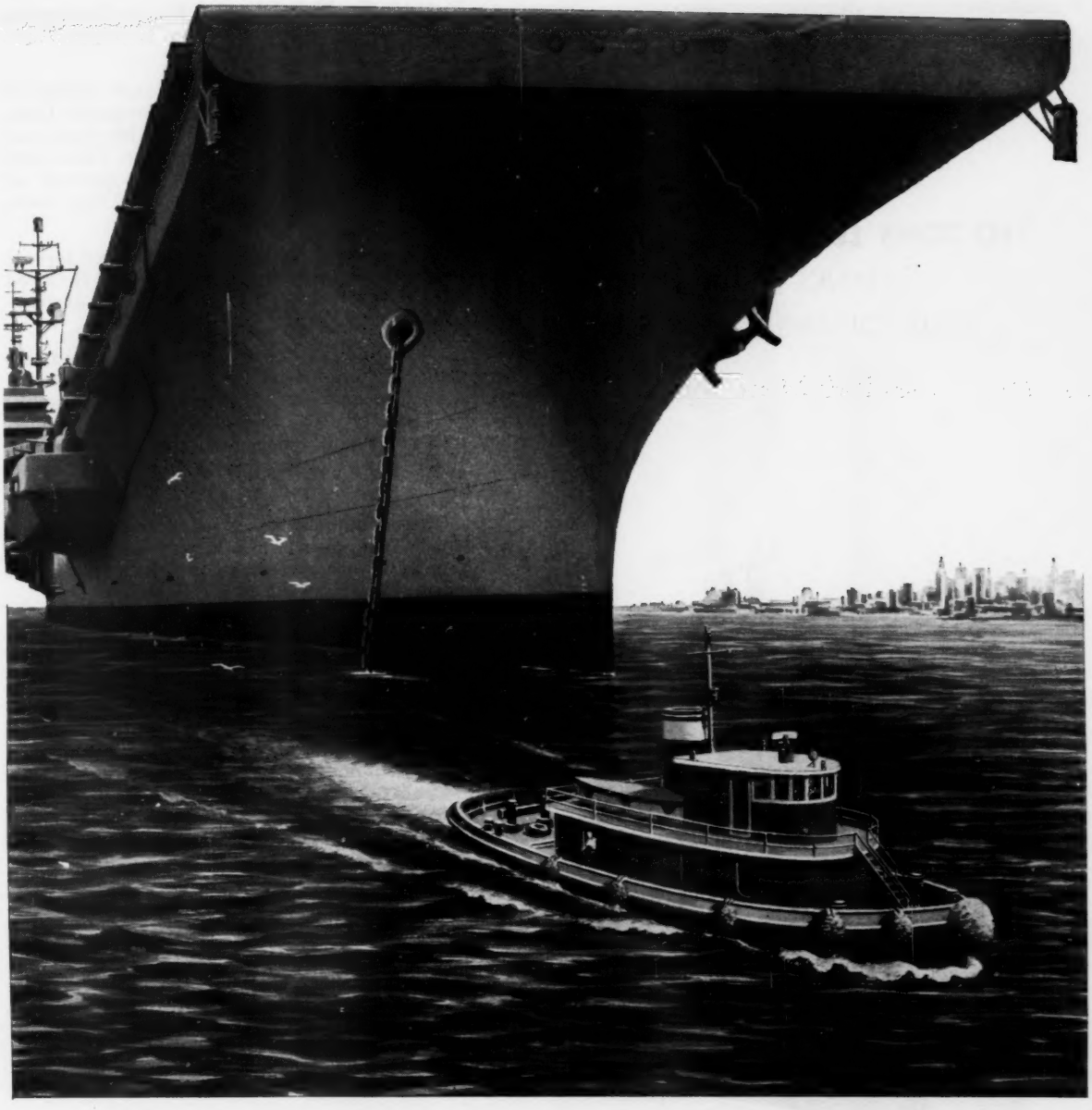

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Like most ships of the U. S. Navy, thousands of commercial and pleasure craft rely on Raytheon radar for safety at night, in fog or storm—in all weather. Raytheon's Model 1500 Mariner's Pathfinder is the *only* low-cost commercial radar built to the same high standards of quality and dependability as military equipment.

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Excellence in Electronics

Raytheon Model 1500 radar consists of only *two* compact, readily-serviced units designed for simple installation and operation. Aboard naval vessels, fishing craft, work boats, ocean liners and yachts, Raytheon radar is logging a consistently superior record of performance and reliability.

RAYTHEON MANUFACTURING COMPANY, WALTHAM 54, MASS.

"10 TONS LESS TOPSIDE WEIGHT
THANKS TO STACKS
MADE OF KAISER ALUMINUM"

To quote Mr. Walter Larsen, Marine Purchasing Agent, Willamette Iron & Steel Company, Portland, Oregon:

"Maximum stability was a major objective when we prepared the Matson Navigation Company's new luxury liners, the S.S. Mariposa and S.S. Monterey for passenger service. That's why light, strong Kaiser Aluminum was selected for the 42-foot stacks, which extend 100 feet above the water.

"The use of Kaiser Aluminum reduced topside weight by an estimated 10 tons per ship. Reduced topside weight is an all important factor in maintaining better stability.

"In addition, the use of aluminum speeded construction. Sections cut easily with a small rotary saw, and aluminum's light weight greatly simplified assembly. The beauty of these streamlined stacks will require only minimum work to maintain, because aluminum is highly corrosion resistant."

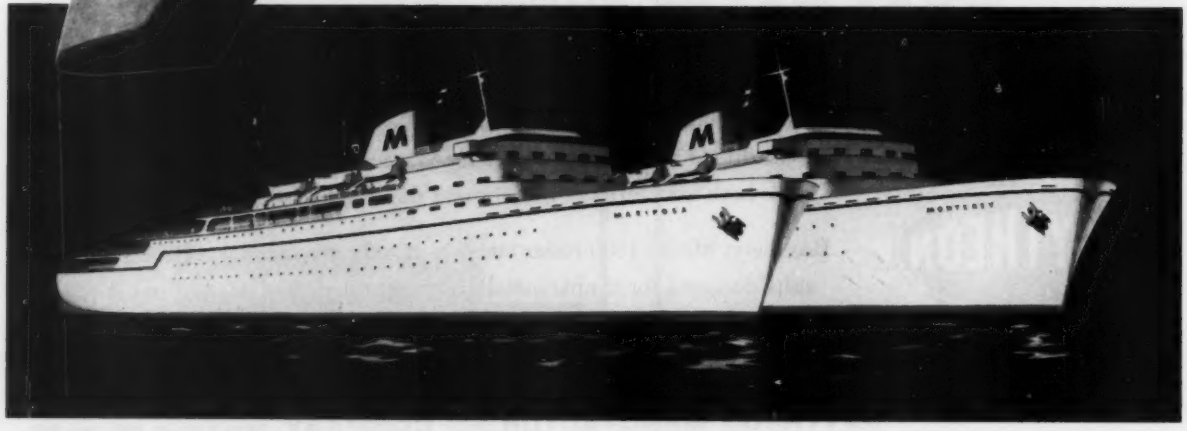
These aluminum stacks are another example of Kaiser Aluminum working with its customers, helping to improve design and reduce costs in the marine industry.

Our Marine Engineering Division will be glad to provide you with aluminum fabrication and design assistance. They will make available to you Kaiser Aluminum's extensive research and engineering facilities.

For immediate attention, contact your local Kaiser Aluminum sales office. *General Sales Office,* Palmolive Bldg., Chicago 11, Illinois; *Executive Office,* Kaiser Bldg., Oakland 12, California.

Kaiser Aluminum

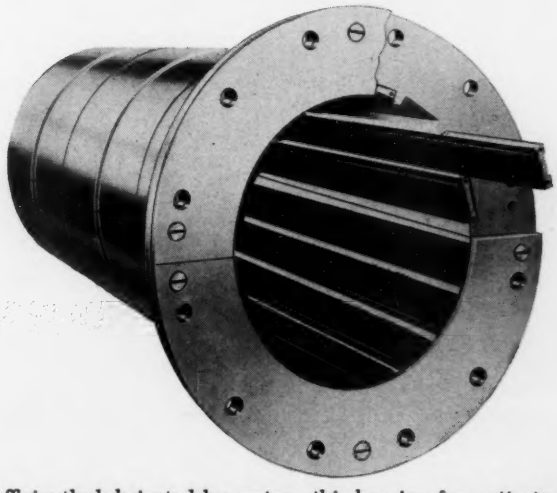
See "THE KAISER ALUMINUM HOUR." Alternate Tuesdays, NBC Network. Consult your local TV listing.



CUTLESS BEARINGS

for

Stern Tubes and Struts



Soft rubber bearing surface—efficiently lubricated by water—this bearing far outlasts all hard surface types, protects propeller shafts, reduces vibration. More than pays for itself in extra wear alone. Saves you time, trouble, and upkeep expense.

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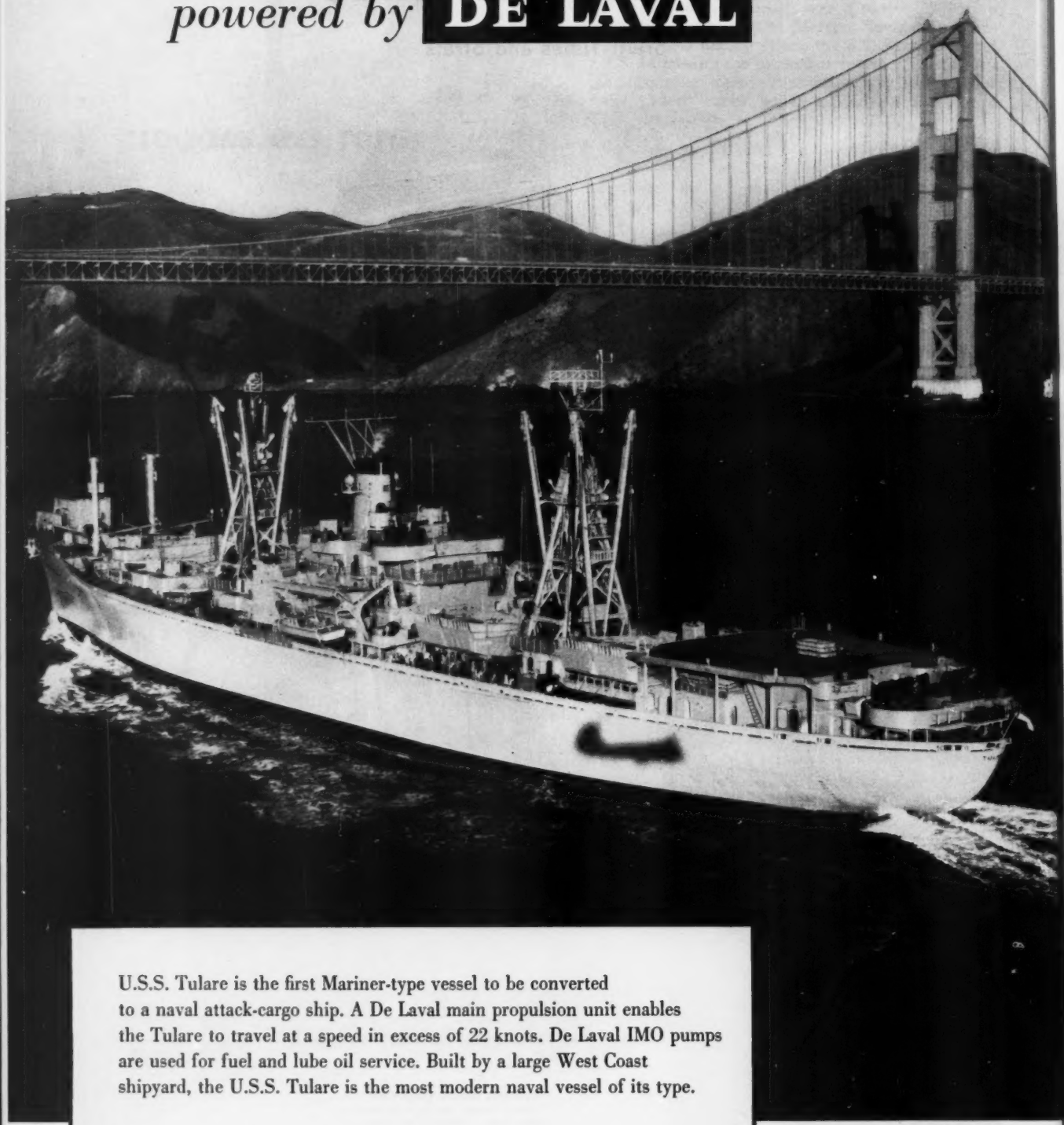
powered by DE LAVAL



U.S.S. Tulare is the first Mariner-type vessel to be converted to a naval attack-cargo ship. A De Laval main propulsion unit enables the Tulare to travel at a speed in excess of 22 knots. De Laval IMO pumps are used for fuel and lube oil service. Built by a large West Coast shipyard, the U.S.S. Tulare is the most modern naval vessel of its type.

Official U.S. Navy photograph

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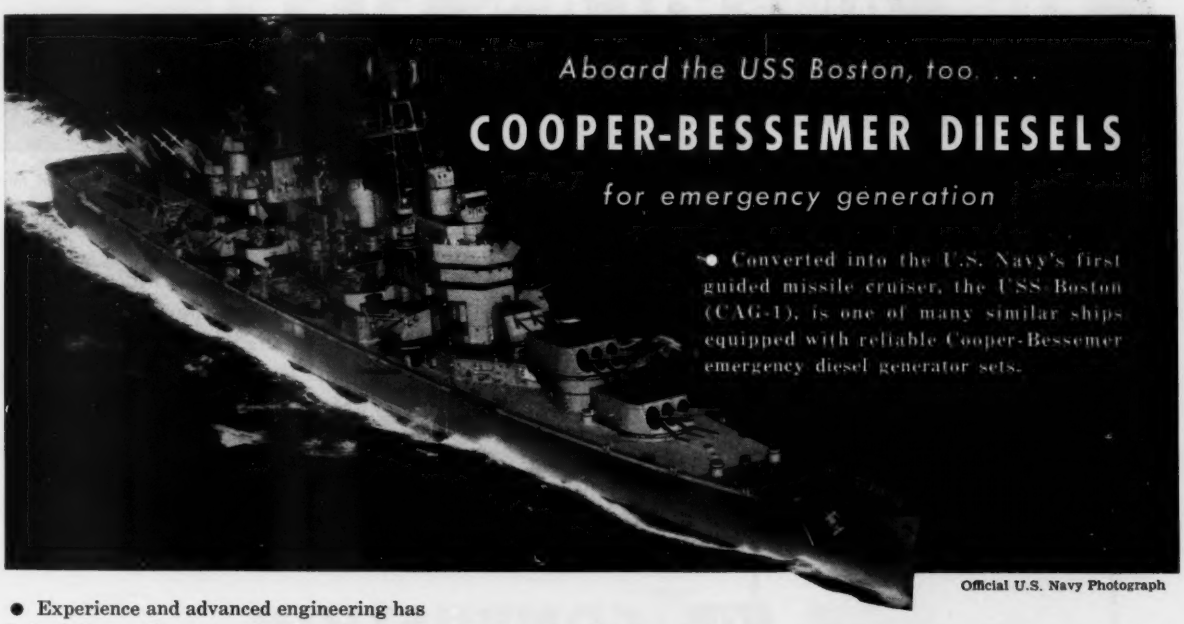
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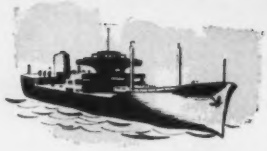
"RIVERS" OF OIL FOR AMERICA'S FLEET

USNS YUKON, largest ship ever built on the Gulf Coast, is launched at Pascagoula, Miss., shipyard of the Ingalls Shipbuilding Corp.



USNS MAUMEE

USNS POTOMAC

USNS SHOSHONE

Four fast supertankers, all named for rivers, will soon be supplying "rivers" of oil to the Navy. Three are being built by Sun Shipbuilding and Dry Dock Company and the fourth by the Ingalls Shipbuilding Corp. These 25,000 DWT "Maumee" class vessels are designed for a cargo capacity of 190,300 bbls. and a speed of 18 knots.

All four supertankers will be powered by C-E Vertical Superheater Boilers, Type V2M – 2 per ship.

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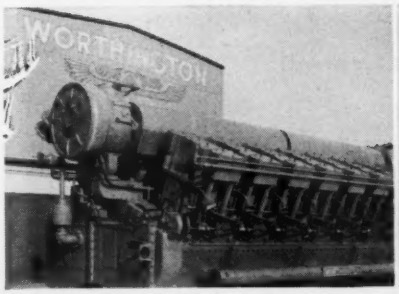
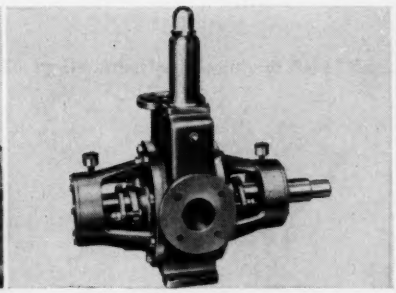
steam generating units; nuclear reactors; paper mill equipment; pulverizers; flash drying systems; pressure vessels; home heating and cooling units; domestic water heaters; soil pipe



Diesel Engines—for shipboard service up to 5,000 hp.



Rotary vane- and gear-type pumps—for handling oil, gasoline and other liquids.

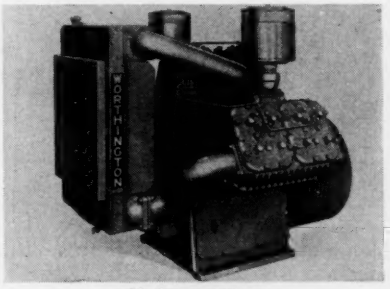
Vertical turbine pumps—for bilge service main cargo and stripping.

Choose from the world's broadest line of shipboard equipment

There are many advantages to selecting shipboard auxiliaries from Worthington's complete line. You can be sure of getting exactly the right equipment to meet your specific requirements. For example, in pumps and compressors alone you have more types than any other manufacturer can supply to choose from. You get the same degree of flexibility in all the many other Worthington products for marine application—some of which are illustrated here.

Worthington welcomes the opportunity to help you with special pumping or power problems. And it offers you the advantage of complete product availability and interchangeability anywhere the world over through the services of foreign Worthington companies. Write, outlining your requirements, to Section M62, Worthington Corporation, Marine Division, Harrison, N. J.

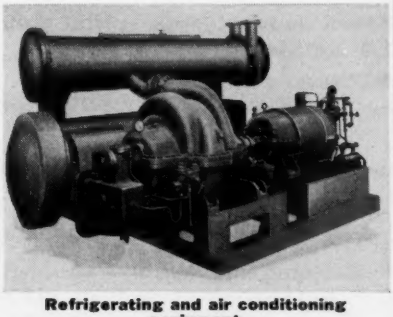
M.6.2



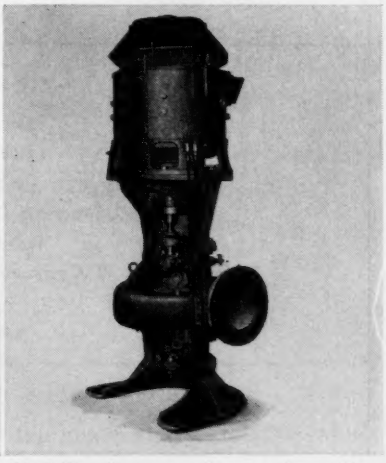
Air Compressors

WORTHINGTON

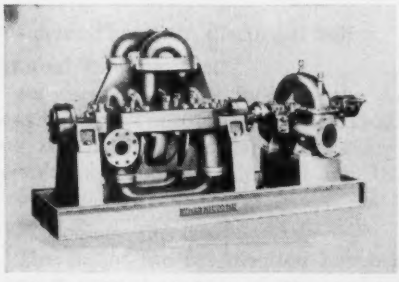
Deaerating feed-water heaters



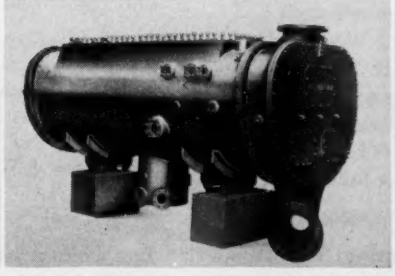
Refrigerating and air conditioning equipment



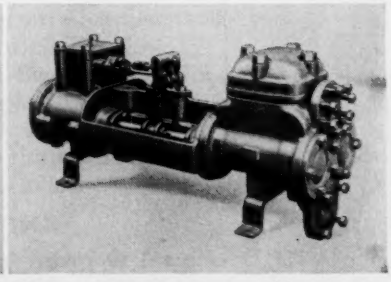
Centrifugal pumps—all types and capacities.



Steam turbines—single-stage, multi-stage, and combined turbine and gear units.



Steam condenser and steam-jet ejectors—for all vacuum services.



Reciprocating pumps—steam-driven, motor-driven and variable capacity units.

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Journal of the AMERICAN SOCIETY of NAVAL ENGINEERS, Inc.

VOLUME 68 NOVEMBER 1956 NUMBER 4

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SECRETARY'S NOTES

Council Meeting, 13 September 1956

The Council held what was probably its last meeting of the year on 13 September 1956. Several important matters were discussed and decisions reached. These are discussed below.

Annual Meeting, 1956

As required by the by-laws, the Annual Meeting was held on Tuesday, 2 October 1956. At this meeting the nominations for officers for 1957 and for membership on the Council for 1957-8 were approved.

1957 Society Election

The ballot for the election has been mailed and should be in the hands of all members by this time. The proposals of the nominating committee which consisted of

Rear Admiral T. C. Lonnquest, U.S.N., Retired, Past President, Chairman; and
Captain W. I. Bull, U.S.N.,
Captain C. H. Campbell, U.S.N.R.,
Captain Joseph B. Duval, Jr., U.S.N., and
Mr. Francis N. Engel, members

were approved at the annual meeting and are included in the ballot as follows:

For President, 1957

Rear Admiral Albert G. Mumma, U.S.N.
Chief of the Bureau of Ships.

For Secretary-Treasurer, 1957

Captain J. F. Hamilton, U.S.N., Retired
Present Incumbent
Captain J. M. Waters, U.S.N.
Director, Value Engineering, Bureau of Ships

For two regular naval members of the Council to serve during 1957 and 1958,

Vice Admiral R. E. Libby, U.S.N.
Deputy Chief of Naval Operations
Rear Admiral R. L. Swart, U.S.N.
Deputy Chief, Office of Naval Material
Rear Admiral B. E. Manseau, U.S.N.
Deputy Chief, Bureau of Ships
Rear Admiral S. N. Pyne, U.S.N.
Assistant Chief, Bureau of Ships (Field Activities)
Captain E. A. Wright, U.S.N.
Director, David Taylor Model Basin

For one naval reserve officer member of the Council to serve during 1957 and 1958

Captain Kenneth Ayers, U.S.N.R.
Western Gear Company
Captain Joseph A. Hartman, U.S.N.R.
Civilian Head, Destroyer and Cruiser Type Desk, Bureau of Ships

For one civilian member of the Council to serve during 1957 and 1958

Mr. John B. Armstrong
Westinghouse Electric Corporation
Mr. Mark W. Swanson
Senior Engineer, Electronics Division, Bureau of Ships

There are no other matters carried on the ballot for decision at this election.

Seal of the Society

When the Society was formed in 1888 an official seal was adopted. The design of this seal has never been changed. Recently the official coloring of the seal, when it is reproduced in color, came up for discussion in connection with the JOURNAL cover and also with a Society flag which is being presented to us.

No record has been found of previous official action on this subject. In 1940, a seal in the form of a pocket piece was used as a favor at the annual banquet. In 1946 a smaller lapel button was purchased and offered for sale to members. At some time a large plaque to hang in the President's office was procured.

Each of these three reproductions of the seal was in color and used red for the leaves and lettering and gold for the background.

Although no record is available, it seems certain that, symbolically, naval engineers are interested in three colors: red, blue and gold. In 1888 the Engineer Corps of the Navy still existed and the majority of the founders of the Society were members of this Corps. These members were identifiable when in uniform, by the conventional Navy blue officers' uniform, with gold sleeve stripes to designate rank. Between the stripes were stripes of red, unique to naval engineers. Also all corps in the Navy have been identified by a corps device which, in each case, is a unique oak leaf design. This was worn on epaulettes and later was placed on the sleeves above the gold stripes, superseding the red as a distinguishing mark. The Engineers' oak leaf is the arrangement which is carried in the center of the Society seal.

Consideration of these facts resulted in the Council's decision formally and officially to adopt a colored seal. It is this coloring which appears on the cover of this JOURNAL. The four elements of the seal are:

The Engineer Corps Device in gold in the center on
A background of engineering red
Surrounded by a gold band and
Closed by a blue circle.

The Society's name and year of founding appear in red on the gold band.

Officially, the Society's name now has "Inc." appended. Advisedly the design of the seal was not changed to include this.

Society Lapel Buttons

In view of its decision as to the colors in the seal, the Council considered the fact that all existing lapel buttons have a different than, now official, coloration. It was decided to scrap the small stock of old buttons on hand and to purchase a new supply in official colors. Notice of this is carried in the Association Notes. It was also decided that a new button would be traded, gratis, for any old button which any member sends in to the Society office. Thus, standardization may be attained without cost (except one way postage) to any member who has invested in one of the old buttons. The button, because of its size will not have the outer blue ring.

Attendance at the Annual Banquet

It was announced previously, that guests at the 1957 banquet would be limited to one for each two members in attendance. This decision has been modified to the extent that the Banquet Committee is authorized to accept applications from single members with a single guest if no request for seating with another party is included. The detailed rates will be included with the banquet applications which will be mailed in about 60 days.

Price of the Annual Banquet

The exact cost of the annual banquet will be determined by the Banquet Committee at a later date. The Council did direct that the differential between members and non-member guests, which has prevailed in the past, would be discontinued.

Captain Dinger

As a follow-up on previous correspondence, Captain Henry C. Dinger, U.S.N., Retired, the Society's oldest living past Secretary-Treasurer called our attention to some errata in the August JOURNAL. These are on page 419 of that JOURNAL:

The Secretary of the Navy referred to was "Newberry" and not "Newburg";

The "member of the Council" was "Strother Smith" and not "Strather Smith";

Admirals Ford and Edwards were *not* on duty in the Bureau of Steam Engineering when they were Presidents of the Society.

Captain Dinger also submitted another discussion which is printed hereafter.

Dr. Lester M. Goldsmith

We have been informed that Doctor Goldsmith, who has been a member of the Society for 18 years, and who is General Manager of the Engineering and Construction Department of the Atlantic Refining Company, has been honored by that company for completion of forty years of service.

Dr. Goldsmith is well-known for his many engineering contributions to the advancement of the petroleum industry. He successfully pioneered the application of electric welding in the construction of pipelines and ocean-going tankers. He engineered the development of the first high-pressure, high-temperature, turbine electric steamship and was later responsible for the world's first class of 30,000 deadweight ton super-tankers used in the oil industry.

During World War II he served as an expert consultant to the War Department and was loaned to the British Ministry of War to participate in the development of their project PLUTO, by which flexible pipelines were successfully extended across the English Channel to supply petroleum products to Allied forces in France. For his services during World War II he received the U. S. Army Exceptional Civilian Service Medal and the Presidential Certificate of Merit.

In addition to many memberships in both civic and professional organizations Dr. Goldsmith is presently doing consulting work for the U. S. Army Transportation Corps.

Manuscripts

The mechanics of submitting manuscripts for publication in the JOURNAL is described in the Association Notes. It may not be clear to many readers "why" manuscripts should be submitted. A full discussion of this "why" would take far too much space for this column. A little bit may be said.

The Society publishes the JOURNAL for the purpose of **the advancement of naval engineering.** This should describe every article which is published.

The Assistant Secretary-Treasurer, each quarter, studies a large number of technical periodicals and selects from a vast number of articles which are deemed to be of interest and value to naval engineers. These, we reprint in the JOURNAL. A bias toward the foreign technical press may be noted at some times. This is done to make available to members articles which may be less accessible to them normally. These reprints help to keep members informed as to advances in Naval Engineering which are initially disclosed through other publications.

Our editorial policy is to divide the contents of the JOURNAL about equally between reprints and original articles. It is relatively easy to select enough reprint material to fill about 100 JOURNAL pages. It is usually very difficult to amass 100 pages of original articles, four times a year.

It would seem that the 3000 engineers who comprise Society membership would generate enough writing to swamp the editor of the JOURNAL. Between them, these members are associated with practically every government, academic, private, industrial and commercial activity which is actually engaged in making advances in naval engineering. In fact, many of these members are personally responsible for the idea or invention in concept which becomes the advance.

Many times, considerations of security preclude an engineering disclosure through JOURNAL pages. It is very improbable that this is a general bar to public writing on *all* important engineering matters. We feel, from our experience in approaching prospective authors, that *security* and *overwork* are merely excuses, easy to use, for covering up modesty or disinclination.

It would seem that a true engineer would be eager to impart his knowledge to fellow society members and that he would want his name to be recognized through his writings with anything which is new and important or worthwhile. At any rate, we wish that they were and that some of them would direct their manuscripts to our attention. Certainly, young engineers can only gain in prestige and in future value by publication of ideas or knowledge.

The original articles which we publish can only be as good as the authors *who submit manuscripts* make them.

Company Membership

We continua ly have difficulty in convincing many members and their employers, that their membership in the Society is a personal affair. *We do not have company memberships.* It is *not* our concern if an employer pays his employees' dues as one of the benefits of employment. It *is* our concern that each payment of dues be clearly identified with the name of the member and that no member consider that his membership may be transferred to another by action of his employer.

Notice to Naval Members

We still continue to have some trouble because members of the Society do not advise us of change of

mailing address. Formerly we were able to obtain addresses of Naval Officers and Naval Reserve Officers on active duty from the Navy Department. This service is now rendered at a cost of $1.00 per address. It is our opinion that expenditure of this amount by the Society in order that members may receive their mail is not justified, and as we have many times in the past, we urge that all members advise us by postcard or other means every time their mailing address is changed.

American Society of Naval Engineers Awards

The Council is happy to announce its decision to make an award each year to the most promising engineer in the graduating class at the service academies which produce naval engineers:

The U.S. Naval Academy, Annapolis, Maryland;

The U.S. Coast Guard Academy, New London, Connecticut, and

The U.S. Merchant Marine Academy, King's Point, New York.

The winner must accept a commission in the appropriate service.

The term "most promising engineer" will not be used in making the awards unless the academy officials wish to use it. The criteria for selecting the successful candidate will be established by the authorities of each school and they will make the selection and, normally, will make the award.

The award will consist of a letter and a check for $100.00 or some object worth about $100.00 if the academy prefers.

Because its graduation exercises are held in August, the Merchant Marine Academy was the scene of the first ASNE award which was made to

Cadet-Midshipman Donald J. Dudziak

with the following citation:

"Cadet-Midshipman Dudziak entered the Academy in August, 1952. During his Third Class year at sea he served with the Mississippi Shipping Company, the Moore-McCormick and the Farrell Lines. His progress reports during his year at sea were excellent in all respects. During his Upper Class years at the Academy he served on the staff of the Academy magazine *Polaris* and was a member of the Rifle Team and the Drill Company. He is a member of the Society of Naval Architects and Marine Engineers, the Propeller Club and the Water Skiing Club. His scholastic average was quite exceptional, having maintained a quality point average of 3.88 which is Number One in a class of 105."

Cadet-Midshipman Dudziak, now Ensign Dudziak, USNR, is a junior member of this society.

Overseas Employment

The Commandant of the Twelfth Naval District has asked that publicity be given to the need for engineers for Pacific Overseas Employment. Openings at salaries from $4,480 to $7,570 per year are available to qualified engineers. Additional information may be obtained from the Navy Board of U.S. Civil Service Examiners for Pacific Overseas Employment, 45 Hyde Street, San Francisco 2, California.

Industrial College of the Armed Forces

Each year the Industrial College of the Armed Forces conducts National Resources Conferences in a number of cities throughout the United States. These have been credited with great value by those fortunate enough to attend them in the past. Because many members of this Society may be interested we reprint below the brochure describing the conferences:

"THE NATIONAL RESOURCES CONFERENCE

PURPOSE

To further an understanding of why this "age of peril" demands the attention of civilian leaders in the fields of industry, commerce, education, government, labor, agriculture, religion, and the professions, as well as reserve officers.

To present, briefly and understandably, the relationship between a nation's economy and its national power.

To clearly define the problems and interrelationships of the economic, social, political, military, psychological, and technological factors affecting our national security.

To highlight the interdependence and the coordination and cooperation necessary between the military and civilian members of our defense team.

PROGRAM

Each conference is a factual and analytical discussion of topics and problems which have a direct bearing on our survival as a nation.

The broad aspects of world political, economic, and power patterns.

The economic ability of nations and blocs of nations to wage war, "hot" or "cold," either with or against the United States.

Material requirements, military, civilian and foreign aid, and the impact on the economy of the Nation of meeting these requirements.

The organization and administration of the Department of Defense, the Office of Defense Mobilization, and other government agencies concerned with national security.

The human resources of the Nation, including the labor force, labor reserve, and the problems of using our manpower in the best interest of national security.

The mineral and material resources of the United States with emphasis on sources and quantities of supply, means of improving our position and the prospects for the future.

The Nation's position regarding energy resources, electric power, coal gas, petroleum, and atomic energy.

Transportation and communication facilities of the country and the problems to be solved in preparing them to meet the requirements of a national emergency.

The Nation's agricultural capabilities.

The problems of production, including capabilities and limitations, over the conversion difficulties foreseen in meeting large-scale military requirements under conditions of an all-out mobilization effort.

The procurement and distribution of military supplies.

The impact of technological progress on the national economy.

The financial and economic stabilization policies, controls, and programs associated with a mobilized economy.

The Mutual Security program.

Public opinion as a fundamental factor in our national strength.

Foreign economic policies and how these policies may be applied in the interest of our national security.

The history and political development of Soviet communism.

The economic and military potential of the Soviet bloc with emphasis on the U.S.S.R.

Each Conference is a factual and analytical discussion of topics and problems which have a direct bearing on our *security and possible* survival as a Nation.

Enrollment

Civilian conferees enroll in the Conference locally, not through the Industrial College of the Armed Forces.

Civilian conferees are chosen by a local Civilian Selection Committee. They are selected as a representative cross section of industry, agriculture, labor, business, the professions, religion, education, women's organizations and civic community life.

Army, Air Force, and Naval Reserve officers, not on extended active duty, who desire to attend the Conference may apply through official channels to their respective Army Area and Air Force Commanders, or Naval District Commandants. Marine and Coast Guard Reserve officers apply respectively to Headquarters, Marine Corps, and Headquarters, U.S. Coast Guard. Upon selection, Reserve officers are ordered to active duty for the period of instruction.

Regular officers and Reserve and National Guard officers on extended active duty may apply for attendance orders through their normal official channels.

Credits

All persons who attend a required percentage of lectures, forums, and discussion periods are presented with a certificate of completion. In addition, military personnel receive active duty training credits provided for by pertinent regulations.

Quotas

Military quotas for each Conference are as follows:

Department of the Army Reserves	50
Department of the Navy Reserves	50
Department of the Air Force Reserves	50
National Guard	6
Coast Guard	2
Local Armed Forces personnel on extended active duty	12
Total	170

Quotas for civilian conferees are limited only by the eligibility criteria established by the Civilian Selection Committee and by the size of the auditorium in which the Conference is held.

Presentation

The National Resources Conference is presented in 16 cities each year by a team of Army, Navy, Marine, and Air Force officers from the faculty of the Industrial College of the Armed Forces.

Each Conference is a 2-week session, 4 hours each day and 5 days a week.

The presentation consists of about 30 illustrated lectures, discussion periods, a few movies, and usually a trip through a local industrial plant.

The Conference is presented so that no prior preparation is required of the conferees.

Each Conference is a condensation of a 10-month resident course given by the College.

Sponsorship

In each city, the Conference is sponsored by a civic group such as the Chamber of Commerce, a local university, or a trade or manufacturers' association, together with the commanding officers of the Army Area, Air Force, and Naval District concerned. The sponsoring civic group *usually* forms two committees, an *arrangements committee and a selection committee.* The arrangements committee selects an auditorium and provides for local transportation, parking, information on housing, meals, etc. The civilian selection committee informs the appropriate local citizens of the Conference and selects applicants for attendance.

Of the 16 conferences in the 1956-57 program, four will have been completed before this issue of the JOURNAL appears. The remainder are at:

Hartford, Conn.	26 Nov.- 7 Dec. 56
Augusta, Ga.	26 Nov.- 7 Dec. 56
Ventura, Calif.	21 Jan. - 1 Feb. 57
Beaumont, Tex.	21 Jan. - 1 Feb. 57
Jacksonville, Fla.	18 Feb.- 1 Mar. 57
Roanoke, Va.	18 Feb.- 1 Mar. 57
San Antonio, Tex.	18 Mar.-29 Mar. 57
Akron, Ohio	18 Mar.-29 Mar. 57
Hutchinson, Kans.	15 Apr.-26 Apr. 57
Providence, R.I.	15 Apr.-26 Apr. 57
New York, N.Y.	6 May-17 May 57
San Diego, Calif.	13 May-24 May 57

Official United States Navy Photograph

Figure 1. USS CANBERRA (CAG2)—The Navy's second guided missiles cruiser.

Official United States Navy Photograph

Figure 2. The aircraft carrier LEYTE, destroyer SARSFIELD and nuclear-powered submarine NAUTILUS at sea during recent anti-submarine maneuvers.

GEORGE LEPPERT

NUCLEAR REACTORS FOR POWER

THE AUTHOR

was born in 1924 and graduated from the University of Wisconsin in 1947. He served in the United States Navy from 1943 to 1946 and is a qualified submarine officer. He received the M.S. (1952) and Ph.D. (1954) degrees in Mechanical Engineering from Illinois Institute of Technology and was engaged in the Reactor Engineering Division of Argonne National Laboratory from 1950 to 1953. Since 1954, he has been in the Department of Mechanical Engineering of Stanford University, teaching courses in heat power and nuclear engineering and conducting research in reactor heat transfer.

THE RECENT AWARD of a contract for construction of a new experimental nuclear reactor brings to seven the number of different types of power reactors being developed by the United States Atomic Energy Commission. This latest addition to the AEC fold is known as the *Organic Moderated Reactor Experiment*, and it represents a parallel effort to the *Liquid Metal Fuel Reactor* and the five basic reactor types chosen for development by the AEC in 1954. The latter, described below, are the *Pressurized Water Reactor;* the *Experimental Boiling Water Reactor;* the *Homogeneous Reactor Experiment;* the *Sodium Reactor Experiment;* and the *Experimental Breeder Reactor.*

It is somewhat arbitrary to categorize nuclear reactors in this manner, since basically they are quite similar. Necessarily, a power reactor must consist of an arrangement of *fuel* nuclei which can be fissioned by neutrons* of various energies with the production of nuclei of lighter elements (fission products); large amounts of useful energy; and fission neutrons which can cause further fissions and thereby sustain the chain reaction. A fluid *coolant* is used to transfer heat from the vicinity where it is produced to a conventional heat engine cycle, and, in most reactors, a *moderator* is necessary to reduce the kinetic energy of the high velocity fission neutrons to low energy thermal neutrons. In many cases, the same substance serves as both coolant and moderator.

Some means must be provided for the *control* of a reactor, both to enable it to follow fluctuations in power demand and to insure safe and reliable operation over a period of time. The most common means of control is the use of control rods which absorb neutrons and thereby "poison" the reactor more or less according to their degree of insertion. However, control may also be accomplished by moving portions of the fuel or moderator to improve or detract from the reactivity of the reactor core.

A further basic function which is performed in some reactors is the *production* or *breeding* of additional fuel from neutron capture by thorium-232 or uranium-238. Although the latter isotopes are not suitable for fuel themselves, their reaction with neutrons leads to the production of uranium-233 and plutonium-239, either of which can be utilized to fuel a reactor instead of the naturally occurring uranium-235.

The seven types of power reactors under development by the AEC, as well as various others which have been proposed, represent different approaches to economical nuclear power production. As various methods of accomplishing the basic functions of fuel arrangement, cooling, moderating, heat transfer, and breeding or production are evolved and combined in different ways, power plant designs are obtained which differ markedly in mechanical structure. This article will describe the designs currently under development in the United States.

PRESSURIZED WATER REACTOR

Naval Propulsion Reactors

Successful development of the Submarine Thermal Reactor installed in the USS *Nautilus* (SSN-571) has given great impetus to commercial and mil-

* For a discussion of nuclear fission and of reactor design for neutron economy, see two earlier articles in this series (12, 13).

itary application of the pressurized water reactor. The STR Mark I, installed in a mock-up of a submarine hull at the National Reactor Testing Station in Idaho, first went critical on 30 March 1953, and generated useful power on 31 May of the same year. Less than one month later, a simulated Atlantic crossing was made without the necessity for a single "surfacing." For all but two hours of this trip the plant delivered full rated power, and at no time was it throttled back to less than half-power (16).

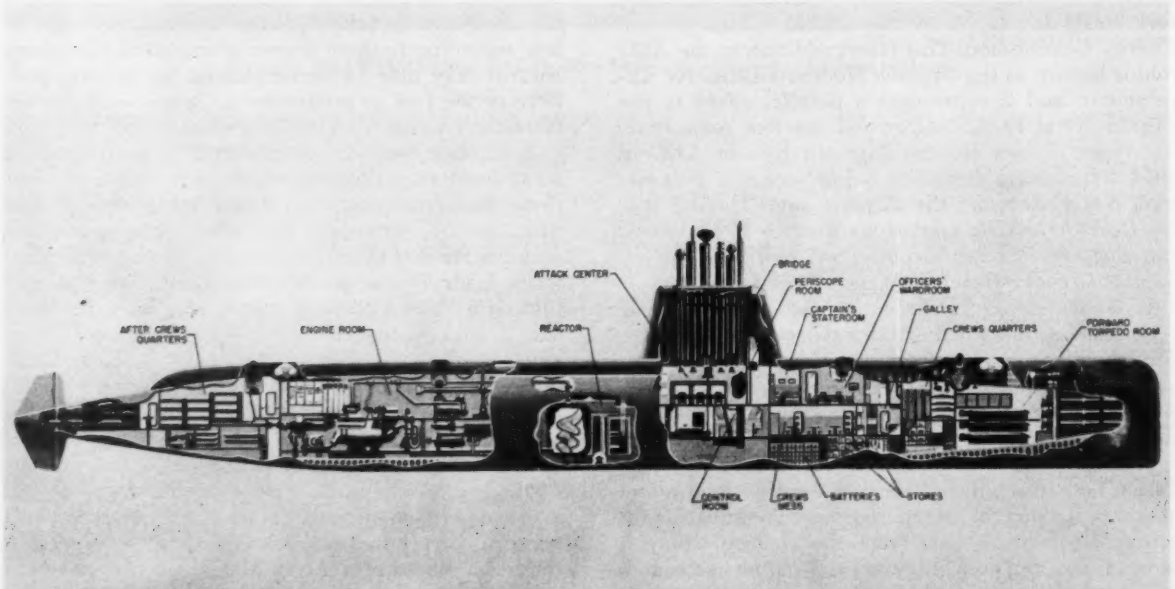
The STR Mark II installed in *Nautilus* has exceeded expected performance, and the Navy has disclosed that no more non-nuclear submarines are planned. Improved versions of the water cooled and moderated reactor installed in *Nautilus* will be provided for both the USS *Skate* and the USS *Swordfish* which are now under construction at the General Dynamics Company shipyard in Groton, Connecticut, and at Portsmouth Naval Shipyard, respectively. The Navy's fiscal year 1957 appropriation bill included six nuclear submarines, two land-based prototype submarine reactors, a land-based aircraft carrier prototype, and a nuclear-powered light cruiser. All of these power plants are of the pressurized-water type which has been proved in *Nautilus,* but they will differ from earlier plants because of the incorporation of improvements and because of the need for plants of various power ratings.

Figure 1 shows a cutaway view of the compartmentation and machinery arrangement in the USS *Nautilus.* The reactor is located in what would be the forward end of the after battery compartment of a conventional submarine, while the turbines and auxiliary machinery are located in the spaces which were formerly the forward and after engine rooms. There is no particular reason to believe that future submarines of this type will continue to have this unusually large engine room; presumably compartments of comparable size to those in a conventional submarine can be provided.

Shippingport Atomic Power Station (PWR)

The first central station nuclear power plant to be built in the United States is the Pressurized Water Reactor at Shippingport, Pennsylvania, which is being built by the Westinghouse Electric Corporation for the AEC and for the Duquesne Light Company (17). Figure 2 shows a cross section of the pressure vessel which contains the reactor. The pressure vessel is 33 feet high over all with an inside diameter of 9 feet. The tank wall is 8½ inches thick with ¼-inch stainless steel internal cladding.

Highly purified light water (primary coolant) enters the pressure vessel near the bottom and is distributed evenly to the flow passages in the bottom plate by a flow baffle. Most of the coolant (90 per cent) flows upward along the fuel elements and is heated, then mixes in the chamber above the core



Official U.S. Navy Photograph

Figure 1. Machinery Arrangement in the USS Nautilus.

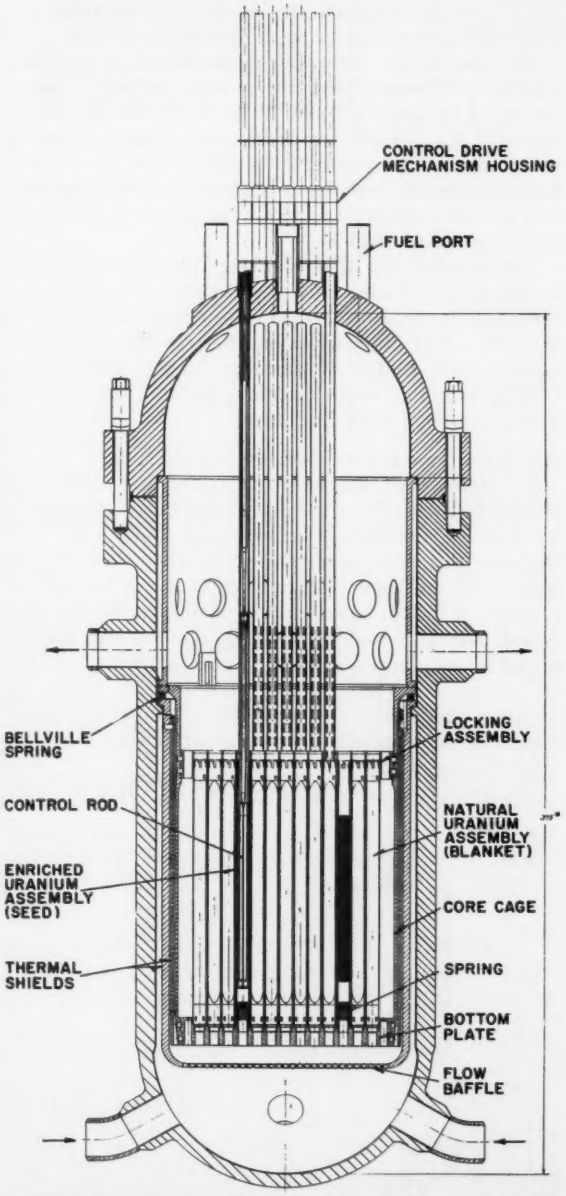


Figure 2. Longitudinal Section of Reactor Vessel for Pressurized Water Reactor (17).

and leaves the pressure vessel. The total coolant flow through the core is 45,000 gpm with a temperature rise from 508° F at the inlet to 524° F at the outlet. In order to prevent vaporization of the water, the pressure in the primary coolant loop is maintained at around 2,000 psi.

Approximately 10 per cent of the primary coolant flow bypasses the core and passes through the annular passages of the thermal shield and next to the pressure vessel. This cooling is necessary because of the appreciable heat generation which occurs in these first layers of shielding and in the vessel wall,

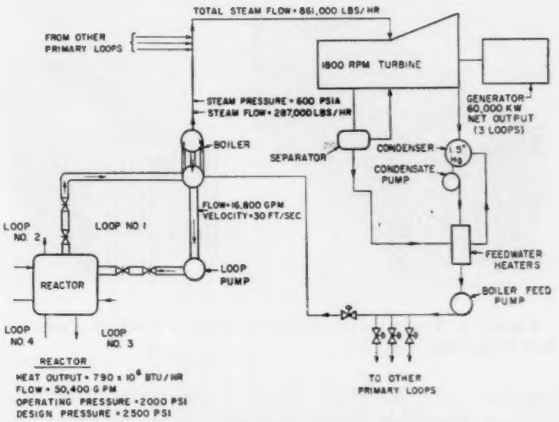


Figure 3. Plant Schematic Diagram of Pressurized Water Reactor (17).

which also serves as a radiation absorber. The biological shielding which is placed outside the pressure vessel is in a region of much lower flux and does not present a serious cooling problem.

The flow of the primary coolant outside the reactor vessel can be seen from the schematic diagram in Figure 3. Four primary coolant loops are provided, each with an inlet nozzle and an outlet nozzle in the pressure vessel, and each with a canned-motor pump, a steam generator or boiler, 16-inch gate valves for isolation of the loop, and connecting 18-inch piping.

Not shown in the flow diagram, but essential to the plant operation, are the pressurizing tanks which are installed in each primary loop. To maintain the primary water in the liquid state at a temperature of 524° F requires a pressure in excess of 840 psia, the saturation pressure. Pressure control at 2,000 psia (saturation temperature 636° F) will be accomplished by means of a large tank fitted with heaters and spray nozzles.

Dry steam is produced at 600 psia in the four boilers, which perform about the same function as in a non-nuclear plant. The remainder of the apparatus in the steam circuit performs the same functions as in a conventional plant, but many of the design features are novel because of inherent differences between the PWR and conventional heat sources.

The Shippingport reactor will produce a minimum of 60,000 kw electrical power from approximately 260,000 kw thermal power, which can be developed using only three of the four primary coolant loops. Most of the U-235 fuel in the core is contained in highly-enriched "seed assemblies" arranged in the core to form the outline of a square. Fuel assemblies away from the region of these seed assemblies contain natural uranium and constitute a blanket where plutonium is produced from U-238.

The seed assemblies contain 52 kilograms of enriched U-235, while the blanket contains 12 tons of natural uranium. The fuel elements in the seed as-

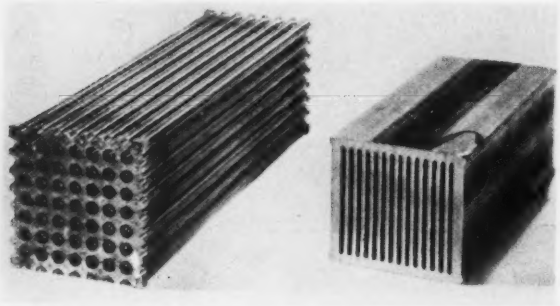


Figure 4. Typical Fuel Element Shapes Used in Pressurized Water Reactor (17).

semblies are 0.080-in. thick plates with 0.080-in. coolant channels, while those in the blanket are 0.413-in. rods on 0.468-in. centers. Figure 4 shows short lengths of typical fuel element shapes (17).

At start-up, 40 per cent of the thermal power will be produced in the natural uranium blanket, and it is expected that this fraction will increase with operating time because of the progressive conversion of U-238 to plutonium. Expected completion of the Shippingport PWR is in 1957.

Other Commercial Pressurized Water Reactors

Another central station plant of the pressurized water type is being designed by Monsanto Chemical Company and the Fluor Corporation for a New England power group, the Yankee Atomic Electric Company. To be located in Rowe, Massachusetts, this plant is being designed for 100,000 kw electrical output, and is expected to be in operation in 1958.

An interesting variation of the PWR is the Consolidated Edison Company reactor which is being designed by Babcock and Wilcox Company (9). In addition to 140,000 kw electrical capacity from a pressurized water reactor, 96,000 kw oil-fired superheater capacity will be installed. This combination will permit delivery to the turbine of 370 psia steam superheated to 1000°F.

The reactor for this plant is fueled with highly enriched U-235 and with thorium which will be internally converted to U-233. The reactor core, which will be a 6-ft. high cylinder 6 ft. in diameter, will contain fuel plates of Zircaloy highly enriched in U-235 and clad with Zircaloy, as well as thorium plates also clad with Zircaloy.

Army Package Power Reactor (APPR)

The United States Army Corps of Engineers has contracted with the American Locomotive Company for the construction of a prototype reactor at Fort Belvoir, Virginia, to test the feasibility of a reactor plant with 1825 kw electrical capacity to be used at remote military bases where delivery of conventional fuel is a major problem. Among the special requirements imposed on this reactor design is that all components be transportable by air, including building and shielding. Assembly of the components would be accomplished at whatever remote site that might be selected.

The prototype pressurized-water APPR is to be in

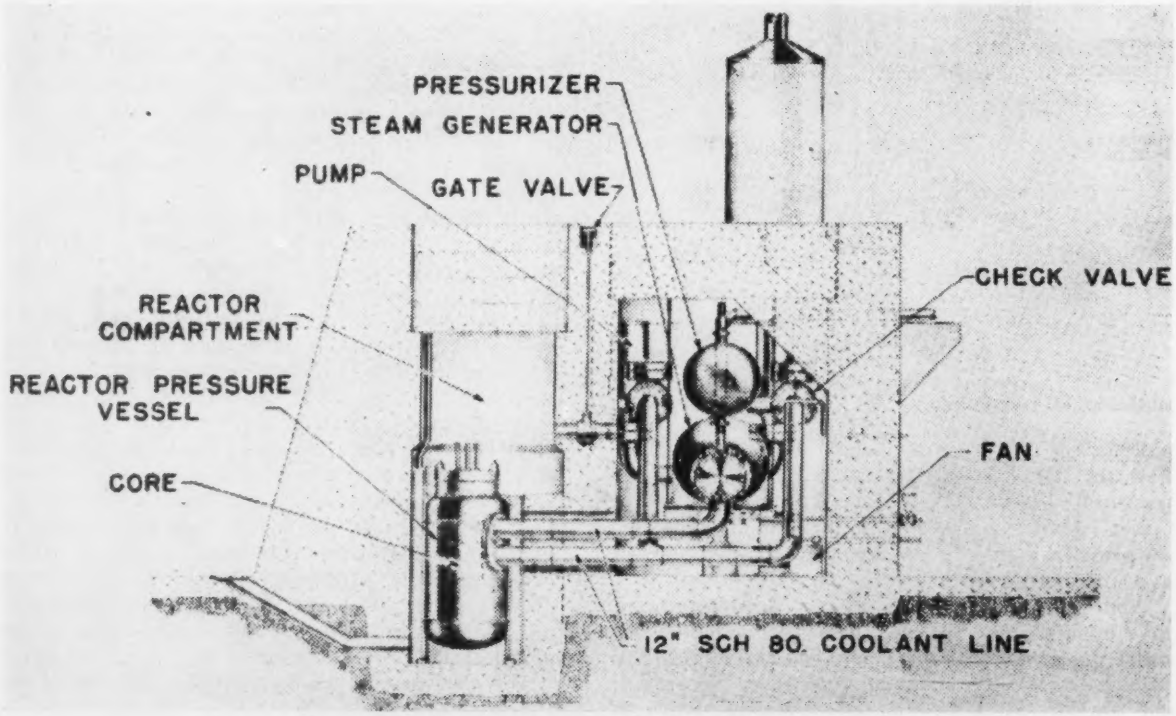


Figure 5. Steam Generator for Army Package Power Reactor (5).

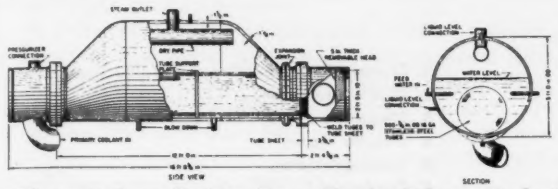


Figure 6. Army Package Power Reactor Primary Coolant System (5).

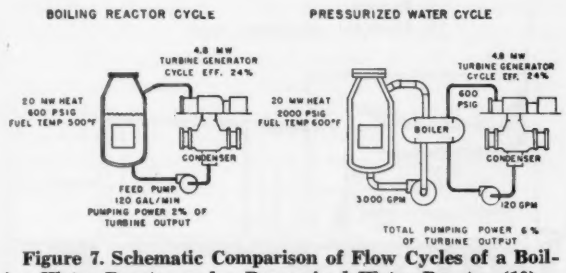

BOILING REACTOR CYCLE
PRESSURIZED WATER CYCLE
4.8 MW TURBINE GENERATOR CYCLE EFF. 24%
20 MW HEAT 600 PSIG FUEL TEMP 500°F
CONDENSER
FEED PUMP 120 GAL/MIN PUMPING POWER 2% OF TURBINE OUTPUT
4.8 MW TURBINE GENERATOR CYCLE EFF. 24%
20 MW HEAT 2000 PSIG FUEL TEMP 600°F
600 PSIG
BOILER
CONDENSER
3000 GPM
120 GPM
TOTAL PUMPING POWER 6% OF TURBINE OUTPUT

Figure 7. Schematic Comparison of Flow Cycles of a Boiling Water Reactor and a Pressurized Water Reactor (10).

operation at Fort Belvoir by 1958. Because of the necessity for containment of the maximum credible nuclear accident and of the desirability of providing on-site training facilities, the building housing the prototype will be somewhat more elaborate than would be provided at a remote location (11).

The original conceptual design for the APPR was prepared at the Oak Ridge National Laboratory (5). Figure 5 shows a cutaway view of the singlepass heat exchanger in which the primary coolant, flowing through the tubes, transfers heat to the vaporizing water on the secondary or shell side. A view of the reactor primary coolant system is given in Figure 6.

BOILING WATER REACTOR

Experimental Boiling Water Reactor (EBWR)

A major simplification is possible in a water cooled and moderated reactor if the water is permitted to

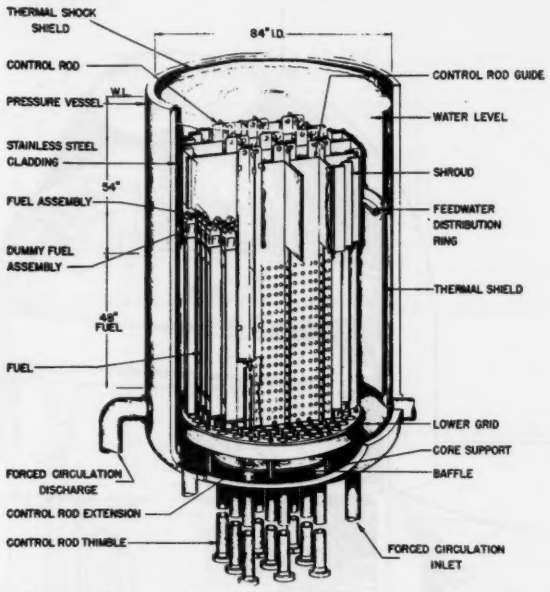


Figure 8. Perspective View of the Experimental Boiling Water Reactor (10).

boil in the reactor core. This permits generation of steam directly from fission energy without an intermediate primary coolant loop and steam generator. Figure 7 shows a comparison of the basic elements of a boiling reactor cycle with those of the pressurized water cycle.

As one of the five basic power reactor development programs undertaken by the AEC in 1954, Argonne National Laboratory has designed and built the Experimental Boiling Water Reactor (10). This plant is rated at 20,000 kw heat or 4,800 kw electrical output. Other design characteristics are noted on Figure 7, which also shows comparable characteristics of a PWR of the same electrical output.

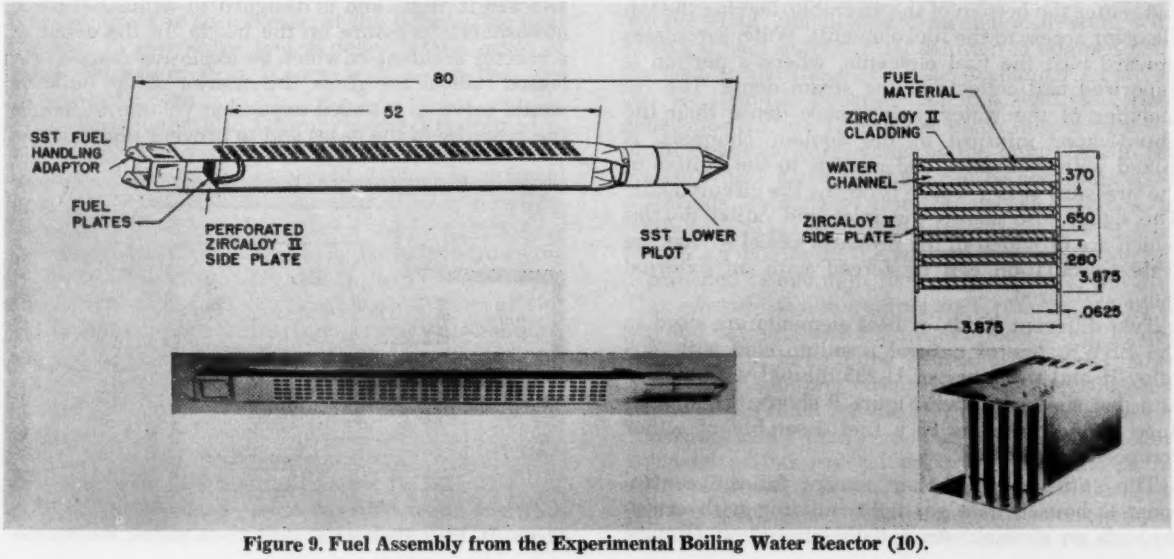


Figure 9. Fuel Assembly from the Experimental Boiling Water Reactor (10).

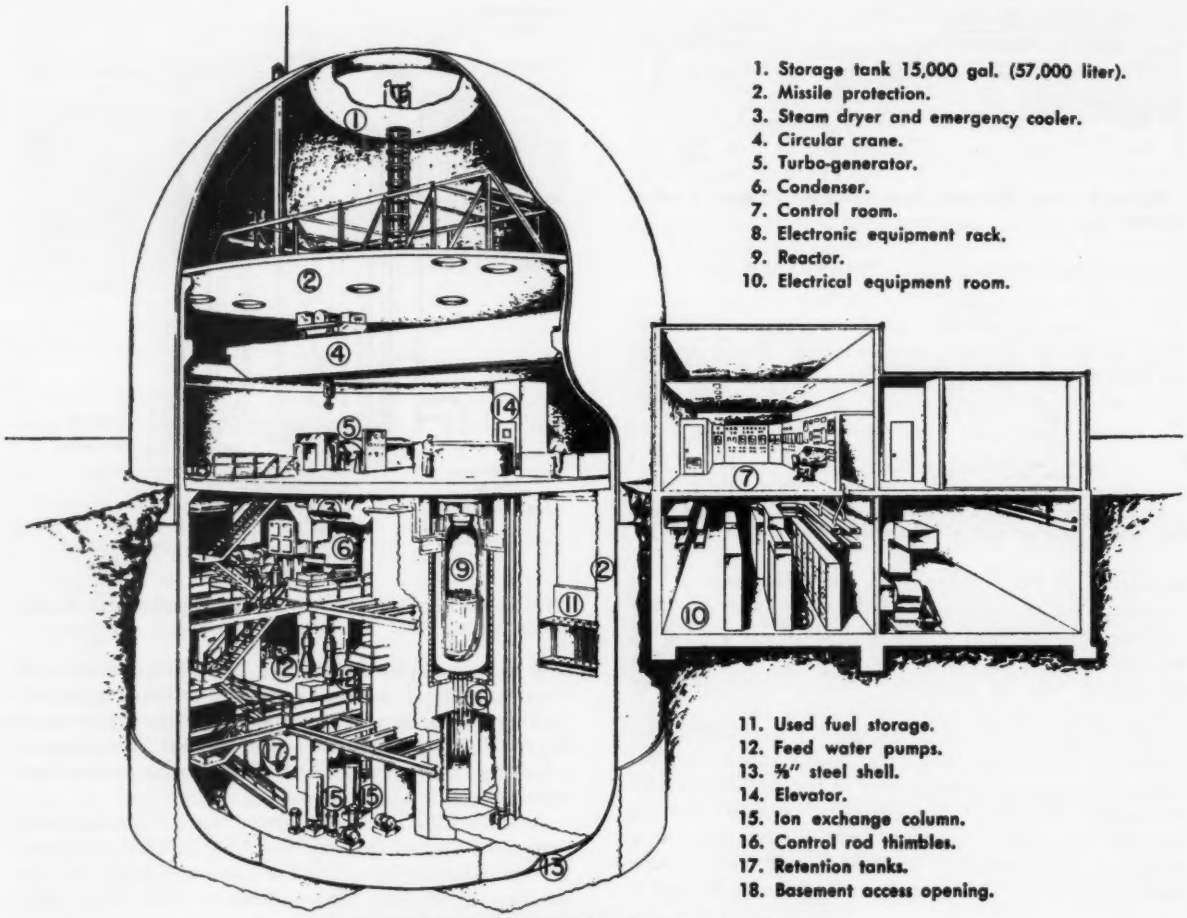


Figure 10. Experimental Boiling Water Reactor Plant (10).

The perspective view in Figure 8 shows the internal arrangement of the Argonne reactor. Control rods enter the bottom of the assembly, leaving the top clear for access to the fuel elements. Water circulates upward past the fuel elements, where a portion is vaporized and collects in the steam dome. The remainder of the water, being more dense than the liquid-vapor mixture in the coolant channels, is mixed with feedwater and returns to the bottom of the pressure vessel where it begins the circuit again. The figure also shows the inlet and outlet nozzles which are provided in the pressure vessel so that the water circulation can be forced with an external pump if desired.

Two different kinds of fuel elements are used in the EBWR, one of natural uranium clad with Zircaloy-II and the other of U-235 diluted with zirconium and similarly clad. Figure 9 shows the appearance and dimensions of a fuel assembly of either composition.

The entire reactor plant except for the control room is housed in a gas-tight building with access through an air-lock. An artist's conception (Figure 10) shows the arrangement of the reactor and auxiliary equipment. The building is 80 ft. in diameter and 119 ft. high, and is designed to withstand twice atmospheric pressure on the inside. In the event of a reactor accident in which an explosive reaction released radioactive gases, the interior of the building would serve as a sealed expansion volume to reduce the pressure of the gases and to prevent their escape.

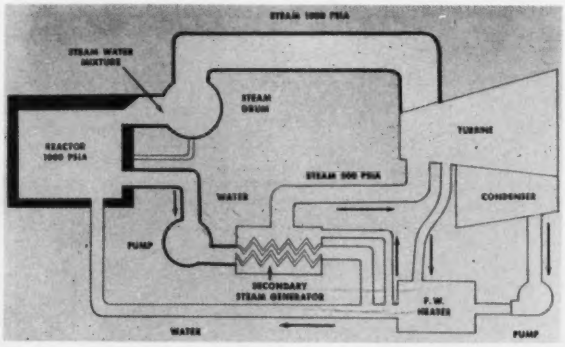


Figure 11. Flow Diagram of Dual Cycle Boiling Reactor (8).

Dual Cycle Boiling Reactor

A full-scale central station plant utilizing a boiling reactor is now being designed by the General Electric Company for the Commonwealth Edison Company. Rated at 180,000 kw electrical output, the Dresden Nuclear Power Station will be located about 47 miles southwest of Chicago and is expected to be ready for operation in 1960 (8).

Examination of the simplified flow diagram for this plant in Figure 11 shows that it differs from the EBWR in that there is a secondary steam generator which produces 500 psia steam by exchanging heat with water pumped from the core. In this way, it is said to be possible to remove more heat from the reactor than if a simple boiling cycle were used. To understand the basis for this statement, consider the operation of a boiling reactor in which the following full-power operating conditions are fixed:

water pressure (hence boiling temperature)
water inlet temperature (less than boiling temperature)
water flow rate at inlet
maximum permissible vapor fraction in reactor

An analysis will show that these factors uniquely determine the power level of the reactor, and an attempt to increase the power generation in the reactor fuel elements will produce an increase in the vapor fraction. Inasmuch as the coolant water is also used as the neutron moderator, and because of the inherent unevenness of bubble formation in boiling, nuclear design considerations impose a maximum permissible vapor fraction in the core.

The dual cycle boiling reactor design is intended to permit a further increase in the power level without increasing the net vapor fraction. This is accomplished by withdrawing a fraction of the water flow from the core where it is at an elevated temperature but before vaporization has begun. Heat is transferred from this water to 500 psia steam, and the primary water is then returned to the reactor inlet, as indicated in the flow diagram of Figure 11. The net effect is an increase in the permissible heat transfer to the water and a delay in the onset of vapor formation to a higher level along the fuel plates in the core.

The Commonwealth Edison reactor is contained in a steel pressure vessel 12 ft. inside diameter and 40 ft. high, designed to withstand 1000 psia internal pressure. Some idea of the difficulty in handling fuel elements which have been used in a reactor can be obtained from Figure 12, which illustrates the proposed remote handling technique for the Dresden station. Observe the provision for a water level (for shielding) well above the reactor core. This handling problem is not peculiar to the boiling reactor, of course, since radioactive decay of fission products in spent fuel presents a handling problem with any power reactor.

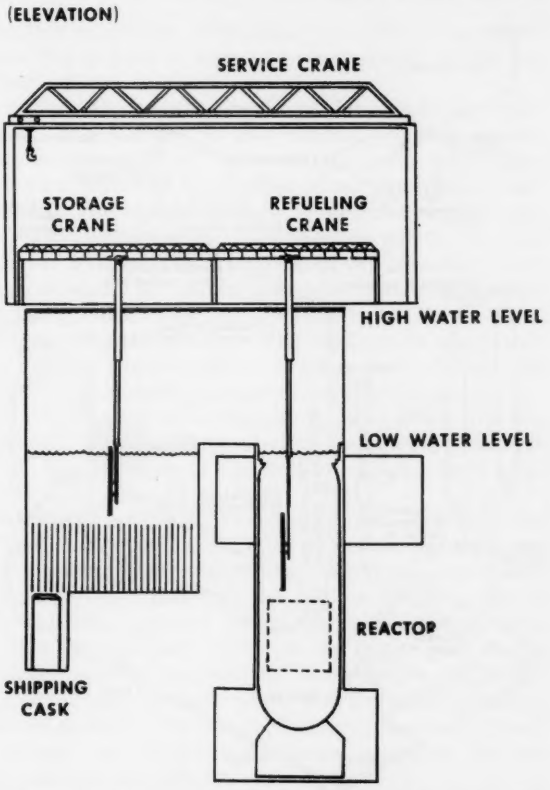


Figure 12. Schematic Elevation of Fuel Handling Apparatus for Commonwealth Edison Company Boiling Reactor (8).

HOMOGENEOUS REACTOR

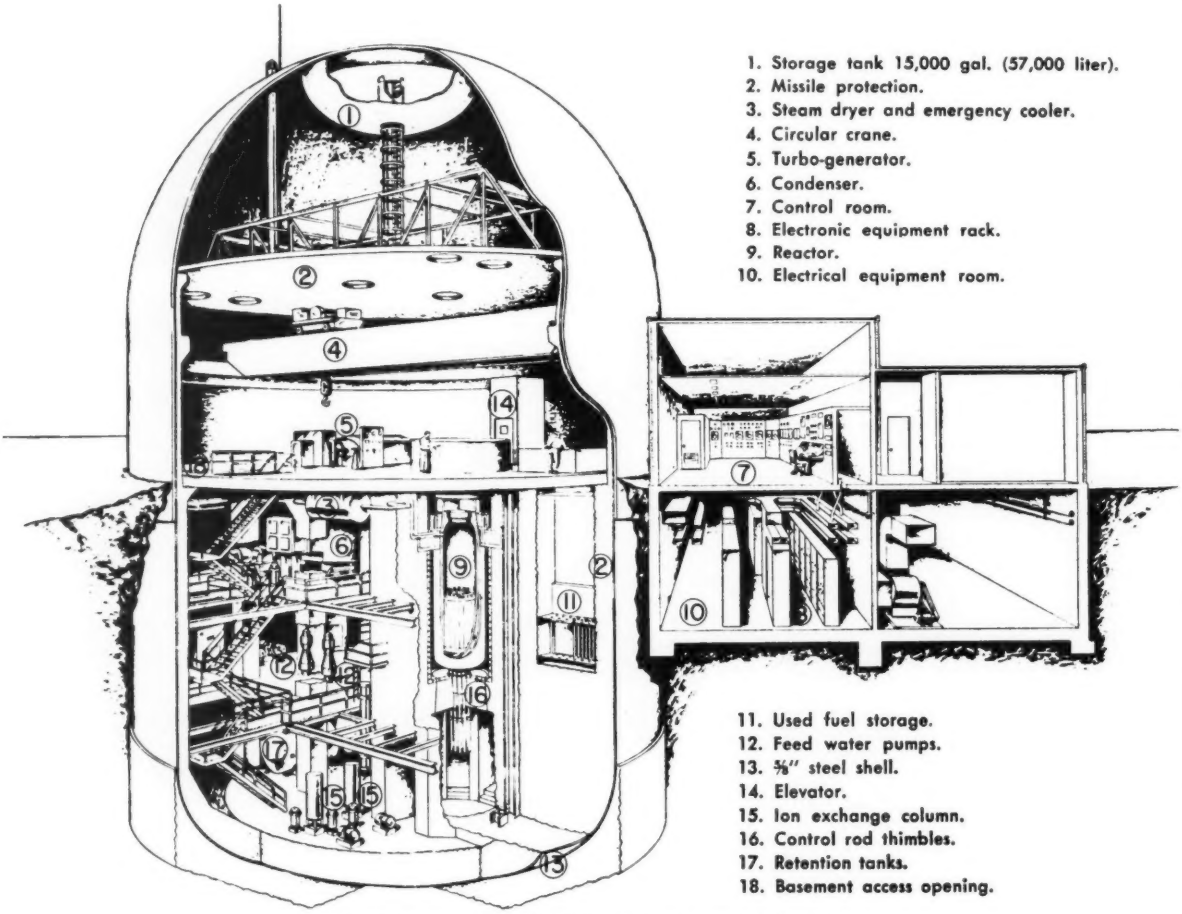
Homogeneous Reactor Experiment (HRE)

A radical departure from the solid metal fuel rods and plates used in the reactors described above is to form an aqueous solution of the fuel. The Homogeneous Reactor Experiment, which was conducted at Oak Ridge National Laboratory from 1951 to 1954, utilized a solution of uranyl sulfate dissolved in water in the core, which was held in a stainless steel sphere 18 inches in diameter (4).

A schematic flow diagram is shown in Figure 13 for the HRE, which was designed to operate with 1,000 kw heat output. Fuel solution is pumped from the core to the tubes of a heat exchanger, in which 200 psi steam is generated on the shell side. Heat generation in the fuel takes place almost entirely in the spherical core, which is the only place in the system where a critical mass can be accumulated.

Various secondary systems are also shown in Figure 13. Since this particular reactor was not intended for boiling in the fuel solution, a pressurizer is provided to maintain 1000 psi pressure in the fuel. This pressure also minimizes the formation of hydrogen and oxygen gases from water decomposition, and a flow circuit is included to recombine these gases. A separate handling circuit with storage tanks and pumps is provided for the D_2O used in the reflector.

Homogeneous distribution of fuel in the moderator-coolant has several important advantages. Instead of shutting down the reactor periodically to replace spent fuel elements, as with heterogeneous types, a small fraction of the fuel solution is continu-



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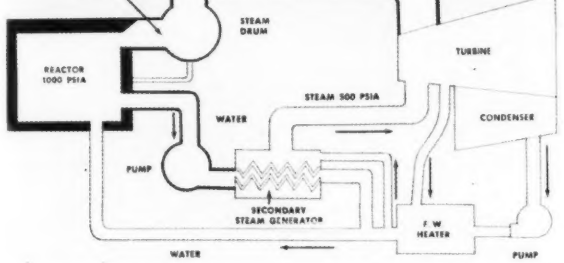

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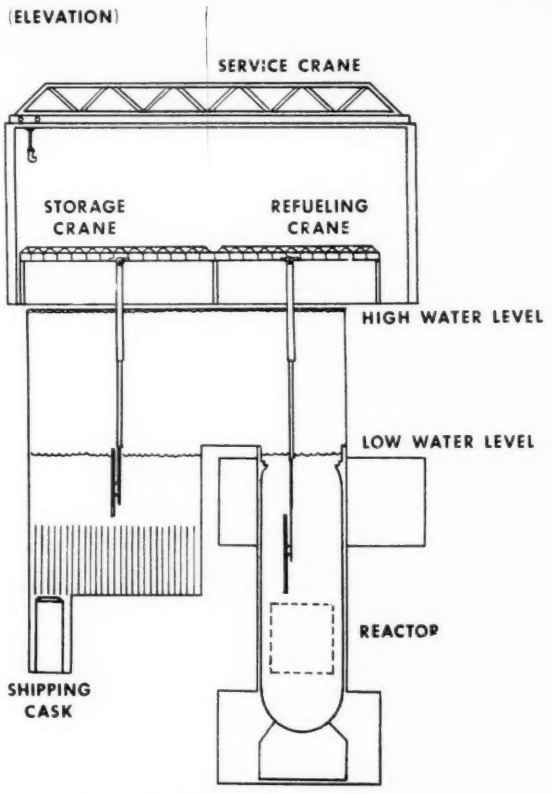

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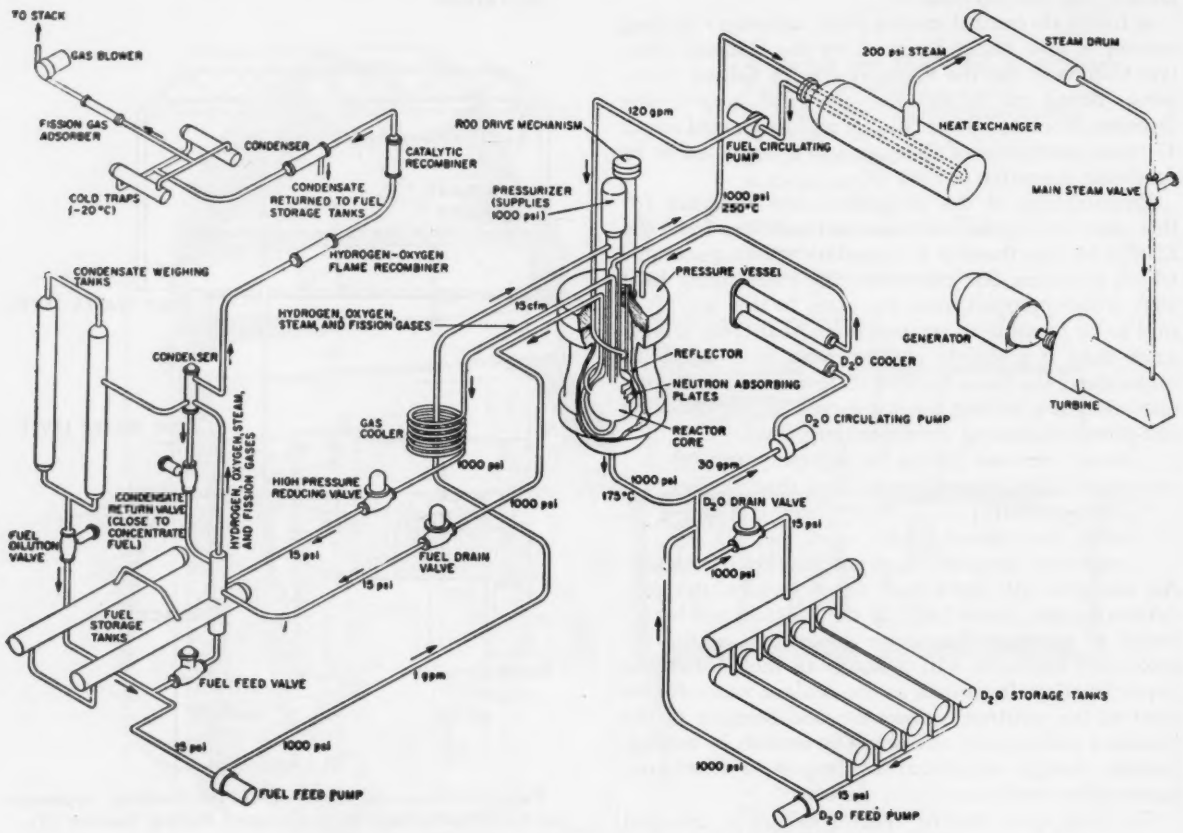

Figure 13. Flow Diagram for Homogeneous Reactor Experiment (4).

ously pumped through a purifying circuit and then returned to the core. Homogeneous reactors are inherently very stable in their operation, with a large negative temperature coefficient of reactivity, and as a result there is no necessity for control rods. The very important problem of heat transfer in the core is greatly simplified because the heat is generated in the bulk of the liquid instead of being transferred to the coolant through metallic plates or rods.

Among the disadvantages to the aqueous fuel solution, in addition to the gas formation when the moderator decomposes, are those of corrosion and of high fluid pressures. As with any water cooled reactor, it is necessary to maintain high pressure in the core if usefully high temperatures are to be realized. At 1000 psia, for example, the saturation temperature of water is only 545°F. Another serious difficulty arises from circulating the highly radioactive fuel solution through pumps, heat exchangers and connecting piping. In addition to presenting a shielding problem, this practice is difficult because of the high pressure and temperature and the corrosive and erosive nature of the fluid.

Homogeneous Power Reactors

An aqueous homogeneous power reactor has been described (6) which is capable of producing 100,000 kw of electricity from a system somewhat similar to the HRE. Important improvements include the use of heavy water in the fuel solution and the addition of a breeding blanket which is a slurry of thorium oxide in heavy water. Figure 14 shows one proposed design for the two-region reactor vessel to be used in such a plant.

The Homogeneous Reactor Test (HRT) at Oak Ridge National Laboratory is intended to demonstrate the engineering feasability of a moderate-sized plant of this type (3). Expected maximum power is 10,000 kw heat in the first phase of the test, which will not include the thorium slurry breeding blanket. The heavy water fuel solution will be pressurized to 2000 psia to minimize the volume of decomposition gas and to prevent boiling. The core tank is a 32 in. diameter sphere of ⅜-in. thick Zircaloy-II.

A homogeneous reactor of 150,000 kw electrical capacity is being designed by Westinghouse for the Pennsylvania Power and Light Company. This plant is scheduled for operation in 1962.

LIQUID-METAL COOLED REACTORS

Sodium Reactor Experiment (SRE)

Another approach to the problem of economical reactor design is an experimental plant which is being designed and built for the AEC by the North

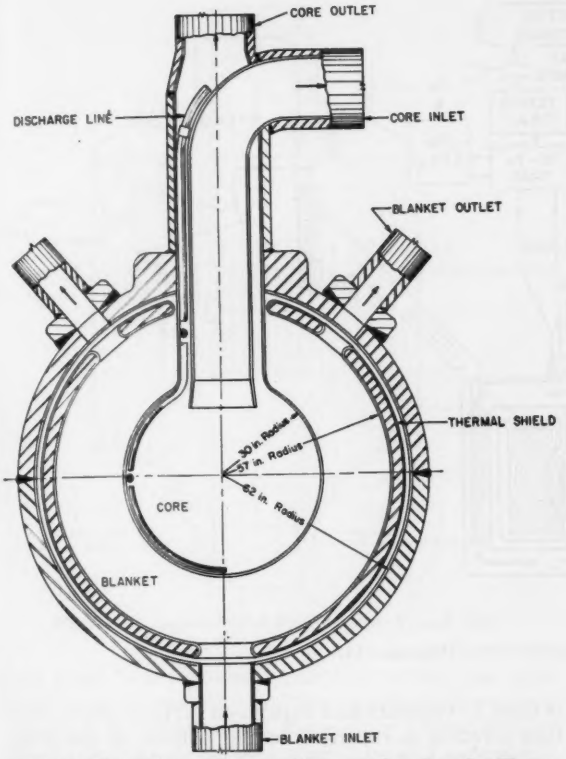

Figure 14. Section of Proposed Two-region Core for Homogeneous Reactor (6).

American Aviation Company at Canoga Park, California (15). This reactor, rated at 7,500 kw electrical output, employs a liquid sodium coolant and "canned" graphite moderator. Graphite is superior to ordinary water as a moderator because of its low thermal neutron capture cross section, and while it is not as effective as heavy water, it is much less expensive.

The sodium coolant can be used at high temperature, which is desirable from the standpoint of thermal efficiency, without the high pressures which are necessary with water. Since sodium melts at 208°F and boils at 1620°F at atmospheric pressure, it is feasible to operate with maximum coolant temperature 925 to 1200°F without pressurization of the sodium system.

Figure 15 shows a simplified flow diagram of the SRE. The sodium in the primary cooling circuit passes through an intermediate heat exchanger where it transfers heat to the secondary liquid metal coolant. The liquid metal in the secondary circuit can supply latent heat and superheat to steam which is used in a turbine. The purpose of the secondary loop is to separate the steam generator from the primary sodium, which is highly radioactive.

Because sodium reacts chemically with oxygen or water in a violent fashion, it is necessary to provide protection against leakage of coolant to the atmosphere and against leakage of water or steam into the coolant. Consequently, a helium blanket is provided over free surfaces of the sodium, and gas-tight construction is used throughout.

A section of the SRE reactor is shown in Figure 16. The primary coolant at 500°F enters the vessel above the fuel and moderator assemblies, and passes downward through pipes to the bottom of the tank. It then passes upward along the fuel elements and collects in the pool shown in the upper part of the vessel, where the sodium temperature is 960°F. Control rods enter through the top of the reactor vessel and fuel element replacement is accomplished through removable fuel element plugs in the top shield and tank lid.

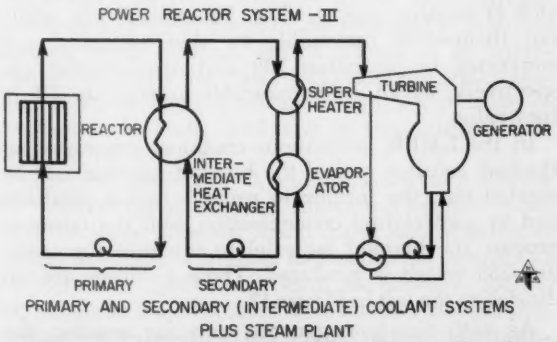

Figure 15. Flow Diagram for Sodium Reactor Experiment (courtesy North American Aviation Company).

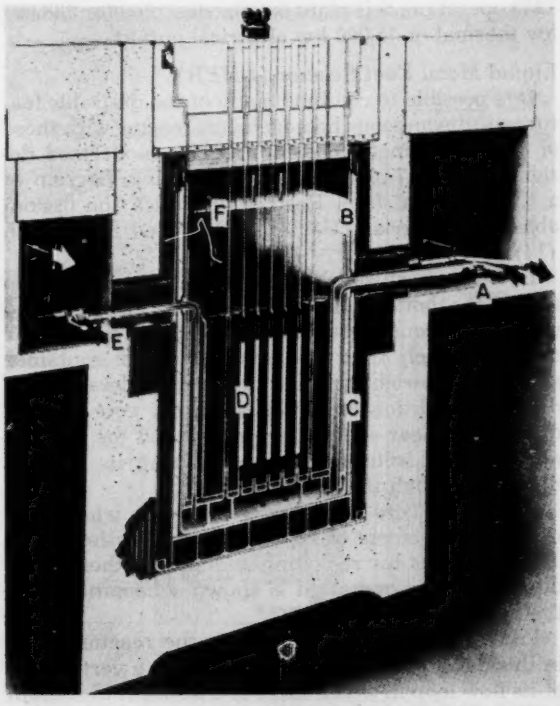

Figure 16. Sectional View of SRE Reactor. A: Main sodium inlet; B: Core tank; C: Thermal shield; D: Fuel element; E: Auxiliary sodium inlet line; F: Sodium level (15).

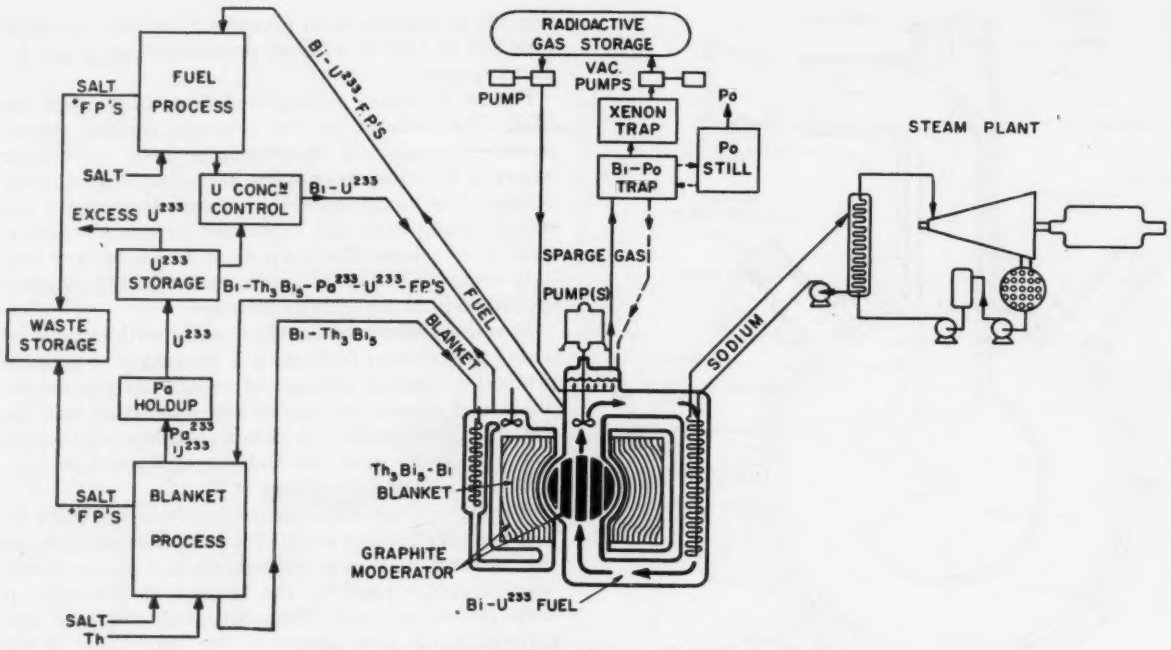

Figure 17. Liquid Metal Fuel Reactor Flow Diagram (14).

A central station power plant of the sodium-graphite design is to be built for the Consumers Public Power District of Columbus (Nebraska) by North American Aviation Company. Scheduled for 1959 operation, this plant is to be designed for 238,000 kw thermal or 75,000 kw electrical output.

Liquid Metal Fuel Reactor (LMFR)

It is possible to combine many of the desirable features of the aqueous homogeneous reactor with those of the liquid metal cooled, graphite moderated design. Figure 17 shows a schematic flow diagram of a Liquid Metal Fuel Reactor, in which the fissionable fuel material (U-233) is dissolved in bismuth (14).

Low-temperature bismuth-U-233 fuel solution enters the bottom of a sperical core chamber and circulates around graphite moderator. The nuclear design is such that the combination of container shape, fuel enrichment and graphite moderator produces a condition of criticality in the core. Consequently, nuclear energy is released, and the temperature of the solution increases during its passage upward through the core.

Above the core is seen a free surface which permits disengagement of xenon and other fission gases. The apparatus for removing and storing these gases during reactor operation is shown schematically in the figure.

From the core, but still within the reactor vessel in this design, the fuel solution flows to a vertical leg of its flow loop in which there is a bismuth-to-sodium heat exchanger. The high temperature sodium from this heater flows to a separate heat exchanger and is used to vaporize and superheat turbine steam. The fuel solution is returned to the bottom of the core, and the cycle begins again. Fuel circulation in this reactor is induced by a pump placed above the core.

A separate liquid metal system comprises the breeding blanket, which is the thorium-bismuth solution which surrounds the core. Because of the very high neutron flux which exists in a reactor core even at moderate power levels, and because of the readiness with which neutrons penetrate matter, it is inevitable that there will be considerable neutron leakage from the core of any reactor. The usual procedure, of course, is to surround the reactor with a *reflector*, which consists of a quantity of moderating material such as water, graphite or heavy water. This material scatters many of the escaping neutrons back into the core.

Reactors with breeding blankets, however, also have uranium-238 or thorium-232 placed in this region of neutron leakage flux. These materials, while not themselves fissionable by slow neutrons, are converted to plutonium-239 and uranium-233, respectively, which are comparable to uranium-235 in fuel value.

In the LMFR, continuous chemical processing of the fuel solution and of the blanket solution will be carried out, the former to remove fission products and to control fuel concentration, and the latter to process the blanket material to separate the uranium-233 which is produced. These facilities are indicated to the left in Figure 17.

As with the homogeneous aqueous reactor, the LMFR permits continuous fuel processing and free-

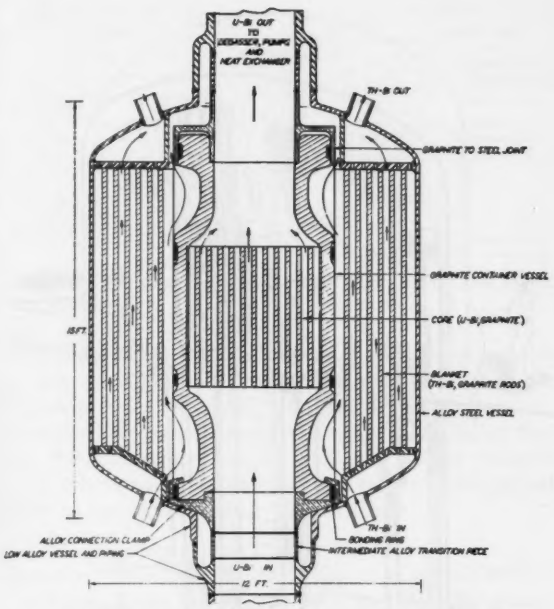

Figure 18. Liquid Metal Fuel Reactor Vessel (14).

dom from heat transfer limitations within the core. Because of the stability and the extremely low vapor pressures of liquid metals, the reactor system will be able to operate at high temperature and essentially atmospheric pressure. These are important advantages and are in contrast to aqueous reactor characteristics. Corrosion by molten bismuth solutions will undoubtedly be a problem, however, and there will be start-up problems presented by the solid state of bismuth at room temperature.

A more detailed idea of the mechanical design features of a large LMFR core is shown in Figure 18. Intended for use with an external heat exchanger, this reactor vessel is sized for a full-scale central station plant. Conceptual design for this type of plant was carried out at the AEC's Brookhaven National Laboratory.

A recently proposed variation of the LMFR is illustrated in Figure 19 (18). In this design, the fuel solution is circulated through vertical steel tubes which are U-shaped. Another liquid metal stream serves to cool these tubes in the core and to transfer heat to liquid sodium, which serves as an intermediate between the core coolant and the steam system. The core coolant in this design is a solution of thorium in bismuth, and it is in this solution that breeding takes place.

Inspection of Figure 19, which is sized for a 500,000 kw thermal capacity plant, shows the reactor vessel with the three different liquid metal flow streams. A typical fuel tube with inlet and outlet connections at the top of the reactor and below the concrete operating platform may be seen. The blanket stream processing line enters from the left. At upper right, intermediate coolant (sodium) flows from the internal heat exchangers to the steam generator and back to the reactor.

Experimental Breeder Reactor (EBR)

One of the most promising approaches to economical nuclear power, and one with some of the most complex design problems, is the fast breeder reactor. Fission is caused by fast neutrons, which means that a number of departures are made from the designs previously described. No moderator is used, since fission neutrons are used directly to produce further fission without slowing down. The probability of interaction of fast neutrons with matter is very low, so the total neutron flux must be much higher in a fast reactor in order to maintain the chain reaction. This high flux may result in serious problems of radiation damage within the reactor. However, since neutron capture cross sections are low, a fast reactor core is much less sensitive to poisoning from fission products. Furthermore, conventional construction materials may be used in the core without the serious neutron loss which would occur in a thermal reactor.

The absence of moderator and the use of conventional materials such as stainless steel in the core permit a substantially smaller reactor to be designed for a particular power output. The smaller the core can be, the smaller will be the neutron leakage from its surface and the smaller will be the fuel inventory. This is a very important economic advantage, but there remains the necessity for heat removal which requires surface area and, conse-

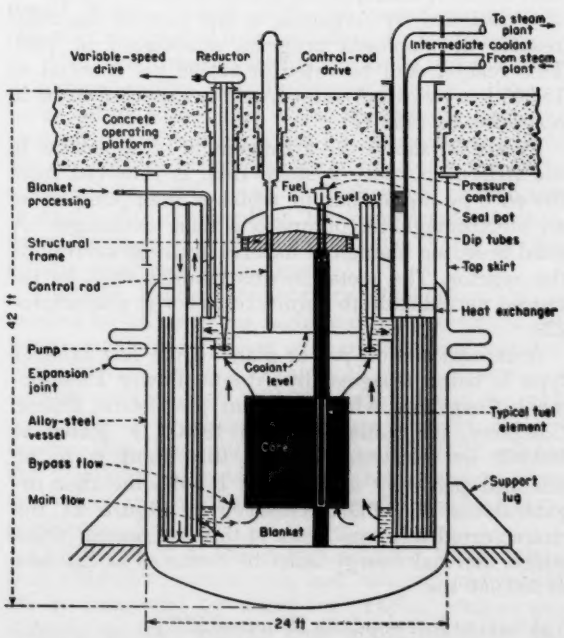

Figure 19. Sectional View of an Internally Cooled Liquid Metal Fuel Reactor (18).

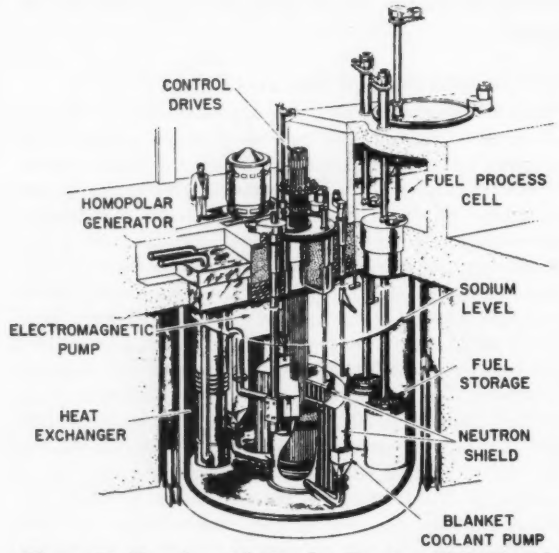

Figure 20. Experimental Breeder Reactor (EBR-II) Primary System (2).

quently, a minimum permissible volume dictated by the effectiveness of the heat removal system employed. It is to be expected that heat transfer considerations will greatly limit the compactness of the fast breeder design but that advancements in technology will continue to be made in this area.

The first Experimental Breeder Reactor (EBR-I) was designed by Argonne National Laboratory and began operation at the National Reactor Testing Station in Arco, Idaho, in 1951. Construction of EBR-II, also designed by Argonne, is one part of the AEC reactor development program announced in 1954. This reactor will be rated at 62,500 kw thermal or 15,000 kw electrical output, and is expected to be in operation by 1958 (2).

Figure 20 shows the arrangement of apparatus in the EBR-II primary system. Heat is removed from the core by liquid sodium, which is then pumped by an electromagnetic pump to a heat exchanger. A solid breeding blanket of natural uranium surrounds the reactor. The metal in this blanket must be removed periodically to permit recovery of plutonium-239.

A central station power plant of the fast breeder type is being designed by Atomic Power Development Associates, which includes the Detroit Edison Company, for construction in 1958 (1). Rated at 100,000 kw electrical output, this plant is to be financed privately and owned by the member organizations of APDA. Observe in Figure 21 the characteristically small core of this fast reactor, from which thermal energy must be removed at the rate of 300,000 kw.

Submarine Intermediate Reactor (SIR)

The prototype reactor for the USS *Seawolf* (SSN-575), know as SIR Mark A, was installed in a huge

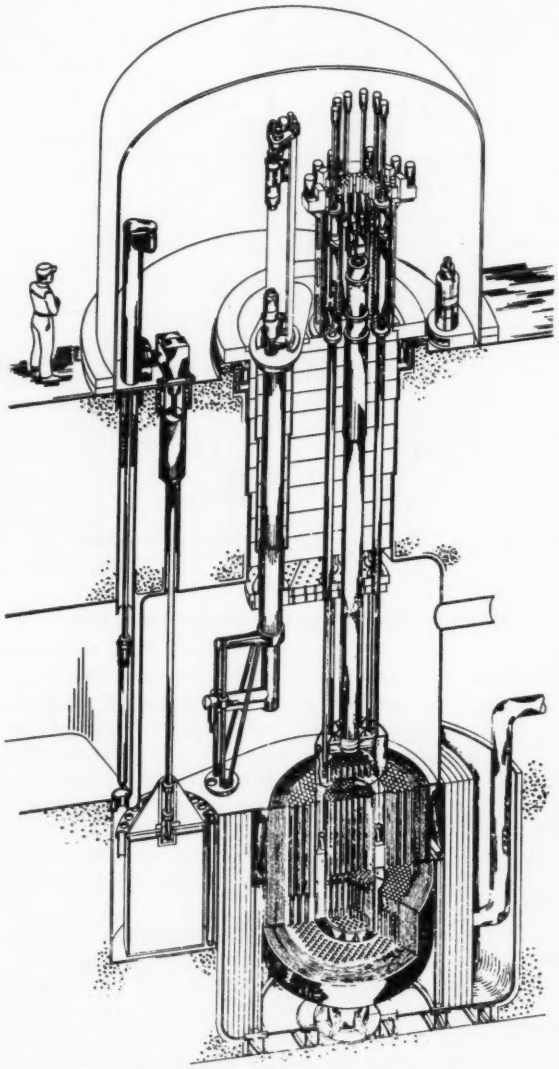

Figure 21. APDA Fast Breeder Reactor (1).

steel sphere 225 feet in diameter at West Milton, New York. Designed and built by the General Electric Company, this reactor is unique in that it is considered as neither a fast nor a thermal reactor. Fission is produced by neutrons in the intermediate energy range between fission and thermal energies. A similar reactor, the SIR Mark B, has been installed in the USS *Seawolf*.

The primary coolant is the SIR is liquid sodium, which is circulated through the core by electromagnetic pumps. It then flows to heat exchangers in which steam is generated. This steam is used to drive turbines and power is transmitted to the screws in the conventional manner.

The use of a liquid metal coolant provides the advantages of excellent heat transfer characteristics and low reactor operating pressure. In addition, the

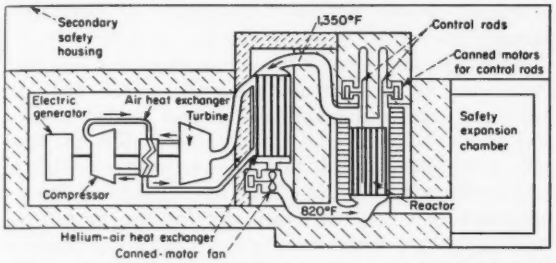

Figure 22. Helium-cooled Reactor Plant with Closed-cycle Gas Turbine (7).

SIR shares with the fast breeder reactor the ability to use conventional structural materials in the core. Consequently, because capture cross sections for intermediate energy neutrons are much smaller than for thermal neutrons, the SIR will utilize stainless steel where many of the thermal reactor designs will have to use expensive zirconium alloys.

OTHER POWER REACTOR TYPES

Organic Moderated Reactor Experiment (OMRE)

As mentioned earlier, the AEC has recently awarded a contract for the design and construction of a thermal reactor which will be cooled and moderated by an organic substance. The recipient of this contract, the North American Aviation Company, will build a plant of 16,000 kw thermal capacity, with completion expected in 1957.

Organic substances, especially the eutectic mixture of diphenyl and diphenyl oxide, have been used in the process industries for many years as heat transfer media. These substances offer the advantage of low vapor pressure for a given temperature. The OMRE, which will use diphenyl, is expected to have a coolant temperature of 530°F as it leaves the reactor, with a system pressure of 300 psi. In order to suppress boiling in a PWR with about the same maximum coolant temperature, a pressure of 2,000 psi is used. The possibility of avoiding such high pressure in the large, high temperature reactor vessel, heat exchanger and associated piping is a very strong inducement to the development of this type of plant.

Since diphenyl is a reasonably dense compound containing the light elements hydrogen, carbon and oxygen, it will be quite effective as a moderator. Unfortunately, it has flash and fire points considerably below the reactor operating temperature, so every precaution will have to be observed to prevent escape of the hot fluid to the atmosphere.

A proposal has been made to the AEC by the City of Piqua, Ohio, to install an organic moderated reactor plant as part of the second round power reactor demonstration program. Sized at 12,500 kw electrical generating capacity, this plant would use only slightly enriched fuel (3 per cent U^{235}) and would generate turbine steam at 410 psi and 550°F.

Gas-Cooled Reactors

There has been interest in this country in a gas-cooled power reactor almost since the first fission

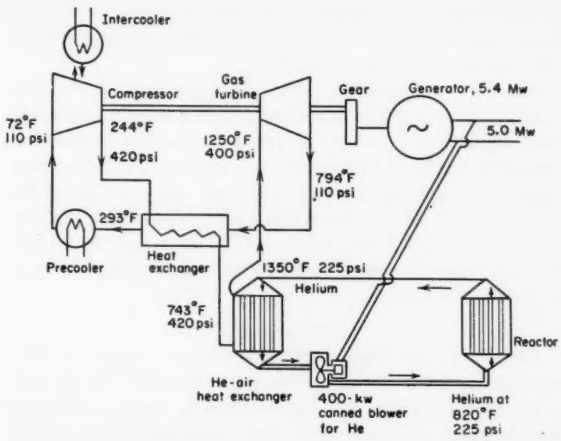

Figure 23. Schematic Flow Diagram for Gas-cooled Reactor (7).

chain reaction at the University of Chicago in 1944. For small and intermediate plants, especially, it might be advantageous to combine the gas-cooled reactor with a gas turbine prime mover, although a steam turbine could also be driven by steam generated in a gas to water heat exchanger.

Figure 22 shows a schematic view of a proposed 5,000 kw plant (20,000 kw thermal), and Figure 23 shows a flow diagram for the same plant design (7). The reactor is cooled by 225 psi helium gas, which flows at 1350°F to a heat exchanger where it transfers heat to air from the gas turbine cycle. The helium returns to the reactor at 820°F.

The closed cycle gas turbine plant is of conventional design except that the usual combustion chamber is replaced by a helium-to-air heat exchanger. Air flows from this exchanger to the turbine, then to a regenerative heat exchanger in which the exhaust air is cooled and air to the helium heat exchanger is preheated (to 743°F). A precooler before the compressor brings the air to the minimum cycle temperature (72°F), and compression is carried out in stages with intercooling. The compressed air then flows through the regenerator and back to the helium-to-air heat exchanger.

The high helium temperature (1350°F) which is needed for efficient gas turbine operation wou'd not be attainable in a reactor with conventional metallic fuel elements. Instead, ceramic elements of uranium carbide are proposed, with the remainder of the core consisting of graphite blocks supported by molybdenum. Use of an inert gas such as helium precludes the possibility of oxidation or other chemical reaction which might otherwise occur at these high temperatures.

Consideration of this design suggests immediately that efficiency, initial cost, and compactness would all be improved by using the reactor coolant gas directly in the turbine. This would eliminate the large, costly helium-air heat exchanger, together with much piping and auxiliary apparatus. This

modification is suggested by the designer (7) for later models after suitable working experience with the more conservative unit.

Another interesting possibility for future consideration with a helium-cooled reactor having ceramic fuel elements is that of using a molybdenum or tungsten turbine at very much higher temperatures than are possible in conventional gas turbines. In the presence of an inert gas only, these metals may be considered for the 3000 to 4000°F range, in which thermodynamic efficiency might well be double that of today's machines.

CONCLUSIONS

Although the basic components required for the production of thermal power from nuclear fission are rather well known and agreed upon, many different power plant designs have been proposed. Although each of these designs has its obvious advantages and, usually, its obvious disadvantages, there is no way to choose between them on the basis of a "paper study" alone. Only actual operating experience will permit an evaluation of their relative safety, reliability and economy.

It is the announced intention of the United States to accelerate the development of commercial atomic power, both for application in this country and abroad. One important part of this program is the construction by AEC laboratories and contractors of pilot plant size reactor experiments, such as the Experimental Boiling Water Reactor at Argonne National Laboratory and the Homogeneous Reactor Experiment at Oak Ridge National Laboratory. These experiments permit the design and test of the most promising power reactor ideas to determine whether they are worthy of development into full-scale power plants.

Another important phase of U. S. reactor development is the Power Reactor Demonstration Program, under which private industry is designing and building nuclear power plants with or without financial assistance from the federal government. These plants are generally of comparable size to modern conventional installations, but they are experimental in nature and are not expected to be economically competitive with their conventional counterparts in the immediate future. However, it is expected that operating experience with these first full-scale nuclear generating stations will provide the basis for early development of economically competitive nuclear power.

As knowledge based on operating experience accumulates, it is reasonable to expect that the superiority of certain designs will assert itself, and some of the reactor types described herein will be discarded. Those which survive will be modified and improved, and new developments in related fields such as metallurgy, heat transfer, automation, and chemical processing will continue to influence strongly the course of power reactor growth.

Although the most obvious market for nuclear power may be for central station generation, the first and most spectacular application was to the propulsion of a submarine, the USS *Nautilus*. For the first time, a compact and durable power source which is completely independent of the ingredients of the atmosphere has become available; for the first time, consequently, a truly submarine vessel has become feasible.

With the success of *Nautilus* has come the application of other types of reactors to submarines. Furthermore, the advantages of a nearly weightless and bulkless fuel supply are being applied to surface warships as well. From here, of course, it is a short step to nuclear-powered tankers and freighters in the merchant service, and it seems certain that these will be a reality in a few years.

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FUELS FOR WATER TRANSPORTATION IN THE SOVIET UNION

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enlisted in the Navy in 1931, and has served continuously since that time. He attended Cornell University and Maryland University, obtained his B.S. degree in Military Science from the latter institute. He has had a wide range of duty assignments, including tours as Engineer Officer and Repair Officer on various ships and tenders. This is his third article to appear in the JOURNAL. *He is currently stational in Port Lyautey, Morocco.*

The materials contained in this article have been taken from Russian language publications. The translations are the work of the author.

"THE PRINCIPAL AIMS of the U.S.S.R.'s Sixth Five-Year Plan are to ensure, by means of the priority development of heavy industry, continuous technical progress and higher labor productivity, a further powerful expansion of all branches of the national economy . . ." These words, spoken by N. A. Bulganin, Chairman of the Council of Ministers of the U.S.S.R. to the 20th Congress of the Communist Party of the Soviet Union, in February 1956, while they served to acquaint the rest of the world with Soviet plans for the future, merely emphasized the difficulties which lie ahead for certain sectors of the Soviet economy.

In particular, the fuel industry is faced with the task of providing the means for firing up the tremendous effort which is presently underway to overtake the West. Yet, according to Bulganin, this same industry failed, during the course of the Fifth Five-Year Plan period (which ended on 31 December 1955) to mine enough coal to keep up with the requirements of the Soviet economy, a failure which created difficulties in maintaining supplies of fuel for industry and transport.

In 1955, of the total Soviet fuel supply, 65 per cent consisted of coal, 22½ per cent of oil, and 2½ per cent of natural gas. Or, putting it another way, of all the sources of energy used in the national economy of the U.S.S.R., in 1936 the share of fuel was 98 per cent, and, at the beginning of the Fifth Five-Year Plan period (1951-1955), despite the successful construction of hydro-electric stations, the share was in excess of 95 per cent.

Despite planned increases in the building of hydro-electric stations, a reported 170 per cent during the period 1956-1960, and despite the reported future "broad construction and utilization of atomic power stations," major emphasis has been, and will continue to be placed on the development of fuel production. Two reasons are apparent for this emphasis: (1) new coal and oil fields have been opened up, and (2) the relatively low cost of production. As was pointed out above, oil, and especially gas, constitute a small proportion of the Soviet fuel supply, yet, according to Bulganin, these are the cheapest and most effective fuels. The cost of producing natural gas, for example is cited as but one-eighth that of producing coal.

The following table provides some indication of the past and future developments in the production of various types of fuels in the Soviet Union:

PRODUCTION OF FUEL IN THE USSR

Type of Fuel	1913	1937	1940	1950	1955	1960[1]
Coal (stone, brown, anthracite), millions of metric tons	29.1	128	166	250	395	593
Oil, millions of metric tons	9.2	30.5	31	35.5	70.7	135
Natural gas, millions cubic meters	..	..	..	8.4	10.4	40
Peat, millions of metric tons	1.7	23.8	32.1	44.3	56.3[2]	..
Wood (for fuel[3]), million cubic meters	68	106	..	..	..	..

Transport, as a whole, is one of the prime consumers of fuels, using very nearly 30 per cent of all so-called "stone" coal mined in the Soviet Union, and almost 75 per cent of all petroleum produced. Vessels of the maritime and river fleets spend more than 20 per cent of total maintenance costs for fuel. Among the self-propelled vessels, as distinguished from the barges, dredges, and other dumb craft which use fuel for local light and power, as well as heat, fuel costs range from 30 to 42 per cent of operating costs.

The maritime and river fleets, on board ship, in ports, and in the industrial enterprises connected with their administration and upkeep, use the following types of fuels, the type frequently dictated by the operational area of the particular fleet and the local availability of the fuel:

Solid: Stone coal, anthracite, brown coal, wood, peat, coke, semi-coke;

Liquid: Gasoline (benzine), ligrone, kerosene, sun oil, diesel and motor fuels, furnace oil;

Gas: Natural gas and generated gas (the latter obtained in the process of gasification of wood, anthracite, and semi-coke).

Soviet writers tend to distinguish three main types of fossil coal: brown, stone, and anthracite, differing as to age, chemical composition, and quality (or properties). The sequence of natural changes in the composition of solid fuels takes accepted forms from the vegetable mass, or wood, through peat, brown coal, stone coal, to anthracite. Some idea of how the various types of fuels are consumed in water transportation is gained from the following breakdown:

USE OF FUEL IN WATER TRANSPORTATION (IN %)

Type of Use	Designated Fuel	Specific Type of Fuel			
		Coal	Wood	Mazut	Motor-Diesel
Vessels of the Transport Fleet	68.6	64.7	35.2	79.5	82.6
Vessels of the Port Fleet	5.2	5.3	7.0	5.2	4.2
Vessels of the Technical Fleet	7.0	7.5	8.3	7.0	2.7
Production Needs of Ports	3.2	3.8	1.0	3.3	2.1
Production Needs of Industry (industrial enterprises and maintenance organizations)	3.9	10.0	7.0	5.0	8.4
Communal Needs and Distribution to Labor	7.1	8.7	41.5	...	...
TOTALS	100.0	100.0	100.0	100.0	100.0

Propulsion installations are installed in the various types and classes of vessels in accordance with rules developed by the Register of the USSR, and once installed are the responsibility of the individual chief engineer of the vessel who receives guidance on operating his installation from the Marine Engineering Service of the specific steamship line or steamship company for which the vessel operates. Certain fuel consumption norms are set, but seldom do the vessels meet them. For example, the fuel consumption norm per 1,000 ton-kilometers of transport work, on the average, is for steamships set at 42-46 kilograms of coal, while the same norm for motorships is 8-9 kilograms of diesel fuel. These norms would appear to be ideals which are never encountered in practice. Nevertheless, planners attempt to use norms such as these to arrive at needs in both finance and supply.

Both of these factors take on added significance when it is recognized that in the Soviet Union it is estimated that 3 to 8 per cent of operational time is spent in taking on fuel. The time consumed is, in general, based on the degree of mechanization of the bunkering facilities. Storage areas, particularly in the river basins, are frequently quite distant from the lowest water's edge in order to avoid being submerged during the spring floods. Frequently the distance from the storage area to the mooring is as much as 200 meters, and it is not unusual for stores to be hauled in carts and handled by hand. Larger ports are, of course, mechanized for bunkering and make use of belt transporters, shore and floating cranes, as well as shore and floating bunkers for large volume needs. Liquid fuels, mazut and diesel, as well as gasoline for smaller craft, are handled by pipeline and hose from both shore installations and from floating barges which may or may not be fitted with pumping equipment.

Wood fuel is widely used as a primary source in shore installations for heating, industrial boiler installations, and partly for the river fleet in areas where timber operations are carried out. Wood is mainly used for fuel on board ships in the Northern, Sukhona, Pechora, Lower Irtyish, Western Siberia, and Lena steamship lines, all of which operate in timber processing areas. Of all the fire wood consumed, 6–7 per cent is burned in boilers, both afloat and

[1] Planned. "Directive of the Sixth Five-Year Plan of the USSR (1956-60)."
[2] Planned. The "Directive" makes no specific mention of fulfillment for 1955, nor is a 1960 goal included.
[3] Calculated only for industry, transport, and partly for communal needs.

ashore. Shipyards engaged in building wooden hulled ships use waste timber for fuel and hence are outfitted with boilers designed to operate as wood burners. Soviet standards set the weight of a cubic meter (with a moisture content estimated at 33 per cent) at 1,500 kilograms. The weight of a cubic meter of dry wood ranges from 340 to 710-kg, depending on the type of wood.

Coal, which varies as to type, chemical composition, and ash content, from basin to basin, makes up a large body of available data, the more understandable when it is recognized that the vast majority of Soviet vessels are coal burning types, particularly on the rivers. For example, Donets anthracite is the principle solid fuel in the central and southern river basins of the European part of the Soviet Union. Hence it has been determined that the most effective combustion of this coal in Soviet boilers occurs when the lump sizes are from 13 to 50-mm.

While operating experience has given the Soviet engineer ample evidence that certain types of coal, e.g., brown coal, leave large deposits of cinders and are, accordingly, not desirable for use on board ship, this same engineer must face up to heat losses due to clinkering and he must fight priming in his boilers because he cannot escape "rational regionalization." This is another way of saying that because of the proximity of the mines to the area of consumption, brown coal from the Artem and Raychikhinsk mines is used on ships operating in the Amur River basin. It would do the Soviet engineer little good to order stone coal types from the Donets, Vorkuta, Kuznets, or Cheremkhova regions. Perhaps his only justification for such an order would be the fitting out of his ship with water-tube boilers, the only type, apparently, in which the use of stone coal is justified. Water-tube boilers are not, however, in general use in Soviet ships, and hence the fire-tube types fitted in ships can, and do, use whatever type is available, be it anthracite, stone coal, or brown coal.

The data contained in the following table relate to the steam production qualities of Soviet boilers using the types of coals indicated. Soviet engineers point out that, even to maintain the low efficiencies quoted, more frequent fire-box cleaning is needed with the poorer coals, that it is more difficult to maintain steam pressure, with the end result a reduced average operational horsepower output for the engines. Finally, as the ash content increases, so too does fuel consumption for the ship per hour per horsepower rating. The end result here is increased bunkering time for all ships, both river and ocean going. For the latter a special problem is created. In order to meet operational commitments, to areas without bunkering facilities, it is frequently necessary to load coal to the detriment of cargo carried on the particular run. Costs are increased and profits fall off.

Relationship Between Quality of Coal and Boiler Efficiency

Name of Fuel	Mark or Type	Ash Content, %			
		10	15	20	25
		Efficiency, %			
Anthracite	Slab, run of mine	70	69	67.5	66
	Seed, pea	66	63	61	59
	Run of mine (less slab)	60	57	55	53
Stone Coal	Slab fat, PS slab seed	66–65	65–63	64–61	63–59
	Long flame seed, SS, G. D gas, long flame	62–60	61–59	60–57	69–56
Brown coal					
Raychikhinsk	Brown	59	57.5	56	—
Artem	Brown	—	58.5	57.5	56

Estimates made for Vorkuta, Kuznets, and Cheremkhova coal indicate that when coal is used, the ash content of which increases from 10 to 20 per cent, the:

(1) Engine horsepower falls from 8 to 11 per cent (the lower figure when Vorkuta coal is used, the higher when Cheremkhova coal is used);

(2) Weight of fuel consumption is increased 16-17 per cent;

(3) Actual reduction per horsepower is 26-35 per cent;

(4) Time needed for bunkering is increased an average 16 per cent of total operating time;

(5) Total cost of maintaining a ship in operation is increased 9 to 15 per cent.

In the river fleet alone, one source estimates that the saving in operational expenses for maintaining coal-burning ships would amount to over 100 million rubles a year if the ash content of the coal used throughout the fleet could be reduced 10 per cent.

Coals mined in various areas are assigned specific designators which are carried throughout Soviet literature on the subject. It is to be noted that when transliterated and translated, letter designators do not necessarily follow the name designation. Thus, coals mined in the Donets Basin are designated:

Type	Initial
Long flame	D
Gas	G
Fat	Zh
Coke fat	KZh
Coke	K
Lean baking	OS
Lean	T
Semi-anthracite	PA
Anthracite	A

In accordance with a designation which occurred in 1954, some of the coal which had been classified as gas coal is now classified "D," for "long flame." In addition to the above, the majority of the coal mined

in the Lisichansk area, as well as others, has been designated as gas coal and bears the designating initial "G."

Included in the coal groupings from the Donets Basin was an independent designator "F" for "fleet," to cover coal Mark PAh (a semi-anthracite fat). Whether this grouping has been retained is uncertain, but as of 1954 there was a group of fleet coals designated for use on merchant ships which was related to a special sub-group of the fat coals, Zh8, which included, among others, coal from Mines No. 4 and No. 21 of the "Stalinugol" Trust, No. 4 and imeni Gorkovo of the "Kuybyishevugol" Trust, imeni Lenina and No. 15 of the "Voroshilovskugol" Trust. A small quantity of Mark G (gas) coal from Mine 2/7 Lidievka of the "Stalinugol" Trust and No. 13 Nikopol-Mariupol of the "Kuybyishevugol" Trust and some others were also included in this category.

Donbas coal comes from over 400 different mines, accounting for an estimated 34.5 per cent of total coal mined in the Soviet Union in 1955. As the various seams are worked changes occur in the types of coal mined, and accordingly, changes occur in the types supplied to consumers. This is true as well for other areas, with the result that periodic revisions of State Standards, or GOST's, are issued. From certain of the Standards we obtain the next table of classifications for coal used in water transportation.

CLASSIFICATION OF DONETS COAL AND ANTHRACITE BY PIECE SIZE

Class	Designator	Size, mm	Mark and Class		
			Long Flame	Gas	Anthracite
Slab (plitnyiy)	P	over 100	—	—	AP
Coarse (krupnyiy or kulak)	K	50–100	DK	GK	AK
Nut (orekh)	O	25–50	DO	GO	AO
Small or pea (melkiy)	M	13–25	DM	GM	AM
Seed (semechko)	S	6–13	SS	GS	AS
Dust (shtyib)	Sh	less than 6	DSh	GSh	ASh
Run of mine, less slab	RSh	less than 100	—	—	ARSh
Run of mine (ryadovoy)	R	no limits	DR	GR	—

In addition to establishing norms for size, as listed in the above table, the GOSTs set quality norms, as in the following table for the Donets basin.

QUALITY NORMS FOR DONETS COAL FOR WATER TRANSPORTATION

Index	For the Merchant Fleet		For the River Fleet			
			Coal		Anthracite	
	Grade 1	Grade 2	Group 1	Group 2	Grade 1	Grade 2
Mark	PZh-PS	PZh-PS	PZh-G	PS	A	A
Release of volatiles, %	35–14	35–14	39–26	12–18	—	—
Ash content, %, not more than	7	10	10	10	10	10
Sulphur content, % not more than	2	3	4	4	2	4
Strength (index of breakage) over	—	—	—	—	70	65
Class by piece size, mm	—	—	Run of mine		AS, AO (100–25), AM (25–13), AS (13–6)	
Piece content (pieces of sizes less than lower limit, %)	—	—	—	—	AK, AO—not more than 8, AM —not more than 10, AS—not more than 15	

Note. Anthracite class 13-6 mm (Mark AS) for use in ships with boilers fitted with fire boxes to accommodate low heat stresses.

The Pechora Coal Basin, together with the Donets, forms the most important supply region for coal for the European part of the Soviet Union, particularly the northern and northwestern areas. The Pechora Basin includes the strata in the areas of Vorkuta, Inta, Kozhva, and Yedzhid-Kyirtyinsk. Coal from the Pechora Basin is included in Marks PZh, G and D (semi-fat, gas, and long flame). This coal has a comparatively high ash content, exceeding 20 per cent in all strata except that of Vorkuta. Sulphur content for all coal mined in the basin is higher than the 2 to 3 per cent indicated as the quality norm for maritime fleet vessels. The coal from Vorkuta is used as the main fuel for the maritime and river fleets, within the limits of transport availability. Vessels operating on the Pechora River, on the other

hand, use coal from Yedzhyid-Kyirtyinsk, whose seams directly abut the river, and provide Mark G, or gas coal.

Recent revisions, contained in GOST 6991-54 (the first digits of the Standard are usually in serial form, the latter two designate the year of publication of the Standard, in this case 1954) classify Pechora coal for the maritime and river fleets under the following marks: D, G, Zh19, Zh10, K14, OS6, T. The meaning of the numerical designations following the type of coal are unknown, but may relate to a specific mine, or pit from whence the coal comes. The same GOST established the specific marks to be used by each type of fleet so as to obtain most economical operation of the installed steam plants:

	Maritime	River
Mark of coal	Zh19, Zh10	Zh19, Zh10, G
Temperature of fusion of ash, °C, not lower than	1200	1200
Class, by size of pieces	Screened with piece sizes more than 13-mm	

The GOST requires that Zh19 be burned with a very strong draft under the firebox, and, at the same time, sets quality norms along the following lines:

	Maritime	River
Mark of coal	PZh	PZh
Ash content, not more than, %	10	14
Piece size, mm	over 13	Over 13
Piece content (pieces less than 13-mm), %, not over	10	10
Ash fusion temperature, °C, not below	1160	1160

Before taking up eastern coals, it should be noted that coal from the Caucasus (the Tkvarcheli seam), Norilsk, and Spitzbergen (where coal is mined by the "Arktikugol" Trust), is used on merchant ships, while river ships use coal from Norilsk, Sangar, and other, smaller areas. A 1954 standard, GOST 6869-54, includes marks G, Zh, and group B3. Merchant ships have been assigned marks Zh and G, screened, with piece sizes over 13-mm, and an ash fusion temperature of not less than 1050°C.

According to the "Directive" the Soviets aim at a big expansion of production of coal in the Kuznetsk, Karaganda, and other eastern coal fields. It is reported that during the Sixth Five-Year Plan many industrial plants and power stations will be built in the eastern part of the country. At the same time large-scale rail construction is supposed to be undertaken. The combination of the two will presumably increase the need for both coking and non-coking coal. There appears to be little doubt that rich deposits of such coals exist in the eastern part of the Soviet Union, and, according to Bulganin, it is possible to develop mines with a smaller capital expenditure and obtain coal at a lower cost than in the European part of the USSR. Certain of the deposits can be worked as open-pit mines, in fact. Even prior to the opening of new veins, the Kuznets has the distinction of being second only to the Donets in volume of coal mined.

This coal is the chief fuel for the river fleet of the Kama, Ob, and Irtyish river basins, providing ample quantities with relatively short hauls needed. Characteristics of the coal mined in the basin are extremely varied, and, in general, appear to be similar to those coals already taken up in detail.

Further to the eastward, fields of importance to the various fleets include those located in Cheremkhovo, Chernogorsk (Khakass), Bukachacha, Raychikhinsk, Artem, and Suchan. Eastern and Far Eastern coals for use in water transportation are designated as Zh and G for merchant ships, while river vessels are assigned D and G types. Ash fusion temperatures are assigned not below 1,200° C and both use coal screened between 13 and 100-mm, with the additional feature that merchant vessels may use run of mine Zh coal. Specific quality norms have been established at:

QUALITY NORMS FOR CHEREMKHOVO, RAYCHIKHINSK (GOST 5967-51) AND SUCHAN (GOST 5966-51) COALS

	Maritime		River	
	Suchan		Cheremkhovo	Raychikhinsk
	Grade 1	Grade 2		
Mark	PZh	G	D	B
Ash content, %, not over	10	15	10	10
Piece size, mm			over 13	over 13
Content of pieces less than 13-mm, not over			15	15
Ash Fusion temperature, °C		1200	1200	1200

GOST 5965-51, which was still valid in 1954, set the following standards for Sakhalin coal used on maritime ships:

Mark	Ash Content %, Not Over	Ash Fusion Temperature
K	12.0	1200° C
G	11.0	1200° C
D	10.0	1200° C
PZh	9.5	1200° C

Sakhalin coal was, however, reclassified by GOST 7026-54 into D, G6, G14, Zh21, K14, T, and group B3. By this Standard both maritime and river ships were assigned the use of coal bearing marks G6, G14, Zh21, K14, the first two coming in sizes from 13 to 100-mm, and the latter two in run of mine. All however, require ash fusion temperatures of not less than 1200°C.

To complete the story of coal in water transportation there have been included in separate tables, two listings, the first of which was published by the

Ministry of the Coal Industry in 1953 dealing with fill weights for various coals, and the second a listing of caloric equivalents for various types of fuels in use as provided by the GOSPLAN of the USSR and published in a 1954 volume on fuels for water transportation.

It has already been noted that priority has been given to heavy industrial expansion, with the inherent need for greater fuel supplies. At the same time greater expansion is demanded of water transportation. During the period 1956-60 the river fleets are assigned the job of hauling 80 per cent more cargo than they did in 1955. Part of the manner in which this increase is to be accomplished is by the addition of 720,000 horsepower in tugs and self-propelled cargo vessels, and 180,000 horsepower in passenger vessels. Simultaneously, the merchant fleet has a 110 percent increase assigned in cargo carriage, with additional vessels totaling thousands of horsepower to be joined to the Soviet merchant fleet in the same five year period. It is, therefore, not surprising that stress is now laid on automation and mechanization in both the coal and oil industries, for the failures of one or the other, or both, will reflect outward and downward, pinching off the supplies that are needed to meet expansion and creating havoc with planned movements of ships and cargoes.

TABLE I

Fill Weights for Coal from Various Fields

Locality	Mark	Fill Weight, kg/m³ *
Donets	PZh	860–1080
	PS	916–1100
	DR	830–900
	DK	800–850
	GR	800–950
	AP	950–1050
	AK	980–1000
	AS	930–1000
	ARSh	1010–1270
Pechora	PZh (over 25-mm)	900–920
	PZh (run of mine)	920–1010
	D	960–1050
	G	930
Kuznets	SS	910–970
	PS	880–920
	PZh	780–850
	G	850–880
Cheremkhovo	D	840–900
Khakass	D	820–870
Bukachacha	G	870–950
Paychikhinsk	BR	800–950
Artem	BR	826–945
Central Asiatic	GR	872–930
	BR	900–932

* Weights indicated are believed to refer to coal in "loose" and "packed" state.

TABLE II

Caloric Equivalents for Various Types of Fuel According to Data from the GOSPLAN, USSR

Locality	Mark and Grade	Heat of Combustion, Large Calories/kg	Caloric Equivalent
	STONE COAL FUEL		
Donets Basin	All grades and marks of stone coal	6455	0.92
	All grades of anthracite	6540	0.934
	GK (500-100 mm)	6790	0.97
	GO (25-50 mm)	6205	0.886
	G (run of mine)	6185	0.884
	D (run of mine)	5310	0.759
	PZh (over 25mm)	7330	1.047
	PZh (run of mine)	6450	0.923
	PZh (all grades)	6580	0.94
	PS (run of mine)	6930	0.99
	AK	7080	1.011
	AM	6540	0.934
	AS	6395	0.914
	ARSh	6445	0.921
Pechora Basin			
Vorkuta	PZh (run of mine)	6260	0.894
	PZh (over 25mm graded)	6660	0.95
Inta	D (run of mine)	4200	0.6
Yedzhvid-Kyirtyinsk	G (run of mine)	5600	0.8
Kozhva	D (run of mine)	4800	0.685
Kuznets Basin	All marks	7000	1.0
	G (run of mine)	6890	0.955
	D (run of mine)	6260	0.895
	PZh (run of mine)	7125	1.02
	PS (run of mine)	7100	1.015
	SS (run of mine)	6980	0.997
Karaganda Basin	All marks	5880	0.84
Cheremkhovo Basin	D (run of mine)	5510	0.787
	D (graded, over 50-mm)	5740	0.82
Minusinsk (Khakass coal)	D (run of mine)	5765	0.824
Norilsk	PZh (run of mine)	5110	0.73
Bukachacha	G (run of mine)	5670	0.81
Gusino-Ozersk	B (run of mine)	4450	0.63
Suchan	All marks	5525	0.79
	G (run of mine)	5235	0.748
	PZh (run of mine)	5795	0.828
Artem	B (run of mine)	3840	0.55
Raychikhinsk	B (run of mine)	3405	0.485
Sakhalin	All marks	6990	0.999
	K (run of mine)	7290	1.04
	PZh (run of mine)	6635	0.948
	D (run of mine)	6415	0.916
Tkvarcheli	PZh (run of mine)	5410	0.773
Tkvibuli	G (for all grades)	4680	0.67
Central Asiatic Basin:			
Tash Kumyir	G (run of mine)	5870	0.84
Sulyukta	B (run of mine)	4820	0.688
Kizelovo Basin	PZh (run of mine)	5600	0.8
Moscow Basin (Podmoskovnyiy)	B		
	BK (graded)	3115	0.445
	PETROLEUM FUEL		
Mazut	all marks	9800	1.4
Motor fuel	all marks	10000	1.43
Diesel fuel	all marks	10150	1.45
Automobile gas (benzine)	all marks	10445	1.49
Kerosene	all marks	10260	1.465
Fuel natural gas	all marks	8400	1.2
	OTHER TYPES OF FUEL		
Firewood with 33% moisture		1302*	0.186
Peat for all regions of the USSR except Ukraine		2870	0.41
Coke from various localities		6500	0.93
Coke dust from various localities		4900	0.7

* Relates to 1 cubic meter.

ERICSSON, STOCKTON, AND THE USS PRINCETON

ACKNOWLEDGEMENT

This article was published in the September, 1956, edition of "United States Naval Institute Proceedings." Its author is Ensign Harry C. Watts, USN.
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NEARLY ALL general histories of the United States Navy contain at least passing mention of the first USS *Princeton*. This vessel, designated a steam sloop, is historically and technically notable as the first warship of any navy to use an underwater screw propeller rather than paddle wheels. At the time of her launching, naval engineers throughout the world showed little enthusiasm for the screw propeller. The *Princeton's* performance, although marred by a serious ordnance explosion in 1844, was sufficient to demonstrate the screw's superiority for new construction.

The *Princeton* was, then, a significant vessel in terms of naval technical evolution. Despite the precedent she established and the 1844 explosion, she has lacked the fascination to compel a thorough study. References in the various naval histories are clearly inadequate. From a study of the two men most intimately connected with the *Princeton*—Captain Robert F. Stockton and the Swedish-born inventor, John Ericsson—it is possible to construct an imperfect account of the vessel.

Transition from sail to steam was itself no easy matter. The New York-built *Fulton* or *Demologos,* launched on October 29, 1814, deserves recognition as the first steam warship. Propelled by a partially enclosed paddle wheel, she attained speeds of six and a half miles an hour, and a battery of thirty 32-pounders promised to serve well against the blockading British squadron off Sandy Hook. The death of Fulton, her designer, slowed final commissioning so much that the *Fulton* was never tested in combat. A vessel of limited range, designed for harbor defense, she had no peace-time value and remained in the Brooklyn Navy Yard until destroyed by a magazine explosion in June of 1829.

Although, she marked a break with tradition, the *Fulton,* untested as an effective warship, had little impact upon contemporary naval planning. England experimented rather more energetically with the possibilities of maritime steam plants, encouraged perhaps by the rising interest in steam locomotives ashore. By 1840 there were several paddle-wheelers operative in the British fleet. The United States failed to follow up the tentative lead afforded by the *Fulton.* A second *Fulton* was built in the early 1830s, but this ship apparently resulted from political expediency rather than a spirit of technical curiosity within the naval hierarchy. In 1838 Captain Calbraith Perry used family influence to secure the construction of the USS *Mississippi,* a ten-gun paddle frigate that met with "great success as a cruising vessel; comfortable, fast, steady gun platform, reliable." A certain number of steam craft were used commercially, but technical limitations slowed any vigorous development of this new motive power.

The heavy, clumsy machinery of that day reduced both the space available in the hold, and the weight that might be allotted to the guns and the sail power, while the big paddle boxes encumbered the gun deck and impaired the sailing qualities of the ship. Without producing satisfactory speed, steam increased the risk of fire. Excessive coal consumption limited radius of action; and the vulnerability of their boilers, engines, and paddle boxes confined the steamers for the most part to service as tugs, transports, and dispatch vessels.

There existed, further, the conservatism somehow inherent in military bodies. Tradition and a certain unprogressive sentimentality blocked with considerable success scattered suggestions that such realistic naval design could surpass the sailing ship. Funnels and coal smoke had no more right aboard a properly-run man-of-war than the beating paddle

wheels. "Sailors were not only incompetent to handle machinery, but considered it beneath their professional dignity to learn, and there were brisk incidents like the 'strike' when seamen refused to hoist out cinders on the grounds that there was nothing about cinders in the articles of war." Such resentment stirred officers even more deeply than sailors. All ships were rigged as conventionally as possible, not only to compensate for the restricted cruising ranges of the existing engines, but also from the widespread hope that steam's uselessness would be demonstrated adequately to hasten its entire removal. Only with the work of Ericsson and Stockton was the new system developed to a point that warranted widespread emulation rather than opposition.

An unsigned biography of Captain Stockton treats most reverently his career in Africa, Mexico, and California, as well as his political activities and his connection with the *Princeton*. In the winter of 1837 Stockton made a trip to England to attend to financial difficulties coincident with the panic. While in England he was introduced to John Ericsson by the American Consul in Liverpool, Francis B. Ogden.

John Ericsson was already accumulating some recognition for his various inventions, and his fame would increase greatly in the years following this meeting with Stockton. He had served as an officer in the Swedish army for a time, but in 1826 he resigned his commission, coming to England to apply himself entirely to inventing. Ericsson's *Novelty*, a locomotive that surpassed Stephenson's *Rocket* in matters of technical innovation, was probably his finest work in the period before his affiliation with Stockton.

From 1833 on Ericsson devoted considerable attion and energy to the matter of naval uses for steam. He stated some years later that the propeller used on the *Princeton* had been designed in 1835. A year later he built and patented a small, screw-driven craft as a practical demonstration of his designs. Francis P. Smith was likewise experimenting with the screw at this time, but because of his relationship with Captain Stockton, Ericsson was responsible for the first application of the screw to a warship. Ericsson's craft, with a length of 45 feet, a beam of eight feet, and a three foot draft, was driven by two propellers five feet three inches in diameter. An earlier loss of power through gear linkages was overcome by directly connecting the engine and propellers. Out of gratitude for the encouragement he had received in the midst of general scepticism, Ericsson named the boat for Ogden. Launched on April 19, 1837, the *Ogden* exceeded ten miles an hour during her first trial run on the Thames. "This miniature steamer had such power . . . that she towed a schooner of one hundred and forty tons burden at the rate of seven miles an hour. and the American packet ship *Toronto* at the rate of more than four and a half knots against the tide."

Technical publications and newspapers in mid-1837 contained warm reports of the *Ogden*, but the British Admiralty, contrary to Ericsson's expectation, showed no interest in his latest invention. Undaunted by this apparent indifference, Ericsson invited the Lords of the Admiralty to be towed in their barge from Somerset House to Blackburn and back by his *Ogden*. The journey was made at better than ten knots, but the Lords were scarcely enthusiastic. Sir William Edward Perry, Comptroller of Steam Machinery for the Royal Navy, "indicated very plainly that though his humanity would not permit him to give a worthy man cause for so much unhappiness, yet that 'he could an' if he would' demonstrate by a single word the utter futility of the whole invention." Ericsson learned within a short time that his demonstration had not won Admiralty support. The Surveyor of the Navy, Sir William Symonds, commented at a subsequent dinner, " 'Even if the propeller had the power of propelling a vessel, it would be found altogether useless in practice, because the power being applied to the stern, it would be absolutely impossible to make the vessel steer.' "

Such ridicule and incomprehension from "the tribe of the 'twill-never-do-its" disheartened Ericsson in spite of the continued support and friendship of Ogden. Captain Stockton arrived in England shortly after this failure. Ogden brought the two men together. Impressed by Stockton's interest and perhaps by his prestige in America, Ericsson set out once more to obtain influential backing for his project. Intelligent criticism of the present use of paddle-wheelers as warships and a description of the direct coupling of engine and propellers convinced Stockton that the Swedish inventor's latest project might be practical for naval use. Stockton, taken for a cruise on the Thames, was much impressed, and, in conjunction with Ogden, provided a thousand pounds for the construction of two iron craft of similar design. " 'I do not want,' said Captain Stockton, 'the opinions of scientific men; what I have seen this day satisfies me.' " Once converted to full approval of Ericsson's ideas, Captain Stockton promised not only his personal support but strenuous efforts to interest the American government. At his insistence Ericsson gave up his efforts to promote his maritime ideas in England and prepared to depart for America, a country that appeared likely, if Captain Stockton were a representative American, to provide a more receptive setting for his work. Stockton's unidentified biographer claims that by himself Stockton "conceived the idea of constructing a formidable steam-ship-of-war, with all her machinery below water line, and capable of carrying such an armament as would make her invincible for defense and the most destructive of all known instruments of war." All other sources, however, indicate that Stockton's role was actually that of patron rather than inventor. The biography, written nineteen years after this London meeting, reflects the emotional coloring of subsequent events.

Before leaving for the United States, however, Ericsson undertook the building of a small steamer

for Stockton; it is not clear whether the second vessel ordered was ever constructed. This seventy-footer, named for Stockton, made speeds of twelve knots during her trials. She was rigged as a schooner and sailed across the Atlantic by a crew of five to serve in the United States as an operating example of what Ericsson could do. New York displayed a lively curiosity toward the little craft upon her arrival in late May, 1838, and she was subsequently used as a tug upon a Stockton-owned canal in New Jersey.

Ericsson terminated a railroad job in England late in 1839 and took up residence in New York on November 23 after a crossing on the *Great Western*. In the meantime Captain Stockton had served briefly as executive officer on Hull's Mediterranean flagship. Return to the United States found him actively involved in the political feuding prior to the presidential election of 1840. Unable to convince the naval commissioners of the desirability of a vessel incorporating Ericsson's ideas and angered by what he interpreted as betrayal of Democratic principles under Van Buren, Stockton campaigned vigorously against the President. Apparently a speaker of much persuasiveness and charm, Stockton created considerable astonishment by his partisan display. On Harrison's death President Tyler, something of a mugwump Democrat himself, offered to make Stockton Secretary of the Navy. The Captain, whether from expediency or righteousness, chose to decline the post, requesting and receiving instead Tyler's order for the construction of an Ericsson-designed warship.

By means of continued persistence, then, Stockton had finally cleared the way for Ericsson to build something more imposing than a tugboat. The Navy Department cut down somewhat the size of the ship Stockton requested, but he summoned Ericsson to Princeton, New Jersey, in October, 1841, and informed him of the plan to construct a screw ship of 600 tons. Ericsson sketched preliminary plans immediately and agreed to draw up detailed plans of the ship and its steam plant. Within a week Ericsson provided the requested plans and estimated the maximum engine cost at $75,000. From this time on Stockton called upon his Swedish genius to turn out needed drawings; all told some 124 of them were involved.

Actual construction of the *Princeton's* hull took place at the Philadelphia Navy Yard while engines were being built in New York. From the keel-laying in early 1842 until completion two years later, Ericsson divided time between the tasks of designing the ship and superintending her construction. Launching took place in 1843, but a considerable length of time was spent in outfitting the *Princeton*. "Of the numerous screw steamers planned by Ericsson, the *Princeton* was the only one built under his superintendence. . . . He was extremely particular about the quality of both materials and workmanship." Throughout this period, while devoting his professional skill and a good deal of expense to his position as builder, Ericsson made no direct arrangement with either Stockton or the government for payment for his services or patented devices. "Stockton gave his assurance over and over again that if the vessel succeeded there would be no difficulty about pay." Ericsson carried out the project without qualms, trusting the promise of appropriate financial adjustment. On February 2, 1844, Ericsson received a payment of $1,150 from Stockton.

The *Princeton*, finally completed, was, in fact, a warship unlike any previously known. Her hull of 164 feet length and thirty feet six inches beam on deck was of white oak. "The peculiarity of her model consisted in a very flat floor amidships, with great sharpness forward and excessive leanness aft." Carrying a maximum load, she drew better than nineteen feet. A power plant weighing 85 tons had been designed to turn Ericsson's screw. HMS *Arrogant*, built five years later, contained a steam system of comparable power but of much greater weight, and its volume of some 2,800 cubic feet far exceeded the 1,700 cubic feet occupied by the *Princeton's* engine. A six-bladed propeller was, as in the *Ogden*, directly linked to the engine without intermediate gearing. Placed below the waterline, the *Princeton's* engines were relatively invulnerable to enemy gunfire. Removal of the cumbersome paddle wheels and their trunks made increased space available for topside ordnance, favorably lowered the ship's center of gravity, and reduced underwater drag. Steam remained, because of limited coal capacity, an auxiliary; the *Princeton* was ship rigged. In place of soft coal, in normal usage aboard contemporary commercial steam craft, she burned anthracite, thereby eliminating the tell-tale plume of black smoke. Fan blowers, located in the bilges, helped to produce better combustion and hotter furnace temperatures, a development that made possible rapid warming up of the plant, obviously advantageous in a man-of-war. Ericsson replaced the previous smokestack with a telescoping funnel. This removed one target for enemy gunfire, and the blowers were capable of replacing the normal stack draft. Further, the stack, ordinarily a somewhat ungainly structure, could not be gotten entirely out of the way while the ship was under sail. Stockton pointed out in a letter to the Secretary of the Navy that the *Princeton* could attack "making no noise, smoke or agitation of the water (and, if she chooses, showing no sail.)"

In armament the *Princeton* likewise showed the impress of avant-garde thinking. Her twelve 42-pound carronades were of conventional manufacture, but the experimental main battery consisted of two 12-inch guns capable of firing balls of 220 pounds. Both were guns "of greater caliber than had previously been known in naval history." One of them, later named the "Oregon," had been designed and forged by Ericsson in England and subsequently

brought to the United States. Finding the wrought-iron transversely weak, the Swede devised the idea of shrinking iron hoops into the breech as a safety measure. Captain Stockton was by this time becoming rather convinced of his own technical prowess, and he undertook the construction of a similar gun, "forged at Hamersley Forge, and bored and finished under Ericsson's directions." This was the "Peacemaker." "It was of the same caliber as the imported gun, . . . but a foot more in diameter and the breech, and much heavier. . . . Great confidence was placed in its strength because of the supposed superiority of American iron." These guns produced results without precedent in naval gunnery. Penetration of 57 inches of oak timber and four inches of wrought iron prefaced all too clearly the development of armor plate that would follow.

Even before being outfitted with her guns, the *Princeton* was shaken down. Her performance equalled Stockton's most enthused claims. "Wherever she appeared, immense crowds gathered to witness her evolutions and inspect her machinery." Perhaps no clearer indication of the ship's capabilities exist than Sargent's description of her race of October 19, 1843, with the highly publicized *Great Western*, the same vessel that had brought Ericsson to New York.

> The Battery and the piers were thronged with an expecting multitude. At her appointed hour the *Great Western* came plowing her way down the East River, under circumstances which manifested more than ordinary effort. She was enveloped in clouds of steam, and of dense black smoke; her paddle-wheels were revolving with unusual velocity, leaving a white wake behind her, that seemed to cover half the river with foam; and with her sails all set, she was evidently prepared to do her best in the anticipated race. As she passed the Battery she was greeted with three hearty cheers . . .
>
> She had left Castle Garden about a quarter of a mile behind her, when a fine model of a sailing ship, frigate-like, appeared gliding gracefully down the North River, against the tide, without a breath of smoke or steam to obscure her path—with no paddle-wheels or smoke-pipe visible—propelled by a noiseless and unseen agency, without a rag of canvas on her lithe and beautiful spars—but at a speed which soon convinced the assembled thousands that she would successfully dispute the palm with the gallant vessel, celebrated throughout the world, and everywhere admitted to be the queen of the seas. Such is the march of improvement in the arts. The newcomer was the United States War Steamer *Princeton*. The agent by which she was moved was Ericsson's propeller. She soon reached the *Great Western*, went around her, and passed her a second time before they had reached their point of separation. In a moment, practical men began to speak lightly of their hitherto favorite paddle-wheel, and the propeller that they had shrugged their shoulders at, and amused themselves with for some years of doubtful experiment, rose into altogether unexpected favor.

Preble provided a favorable estimate of her characteristics in a seaway.

> At sea she worked and steered admirably, either under sail alone or with sail and steam. She was a very dry vessel, but, owing to the sharpness of her hull fore and aft the midship section, she pitched in a rough sea with great violence. With a fair amount of canvas and a moderate wind she would careen to an extent unusual in a vessel of her class, but, though she thus easily went down on her bearings, it took additionally a very large quantity of canvas and a strong wind to depress her sensibly further. In a heavy gale clawing off a lee shore she carried sail to a greater extent than was considered prudent by other sailing sloops of war in her company; all of them, and some frigates, she beat out to windward, dragging her propeller.

On February 5, 1844, Stockton, in command of the ship at Philadelphia, sent a description to Secretary of the Navy Henshaw, concluding that, because of improvements embodied in the *Princeton*, "the ocean may again become a neutral ground, and the rights of the smallest as well as the greatest nations may once more be respected."

With the process of equipping and arming finally at an end, Stockton proudly took the *Princeton* to Washington for display to her most critical audience. Stockton's dual position of promoter and captain was sufficient to make him something of a hero in the eyes of press and public, and he was not from all indications a man to reject praise. There is no evidence to suggest that Stockton made an effort to secure due recognition for Ericsson. The members of the House of Representatives were taken for a voyage down the Potomac on February 20, during which the Congressmen were entertained with a feast and gunfiring.

Such was the success of this first cruise, in fact, that a second was arranged for February 28. President Tyler, his Cabinet, and various lesser notables were aboard for an outing similar to that of the previous week. "The day was spent in feasting, romping, dancing, and singing, with music that was almost unceasing, and mirth that was infectious and uncontrollable. During the passage down, one of her large guns . . . was frequently fired, to the enjoyment of all on board." Late in the afternoon as the *Princeton* once again headed upstream for Washington, the new Secretary of the Navy, Thomas W. Gilmer, suggested a final firing of the main battery. Captain Stockton went on deck to command the crew of his "Peacemaker," and a group of yet-curious passengers clustered about the big gun. As the powder charge ignited, the gun burst at its breech, killing Secretary of State Upshur; Secretary of the Navy Gilmer; Captain Kennon, Chief of the Bureau of Construction and Equipment; Virgil Maxey, a former diplomat; a Colonel Gardiner of New York; and one of Tyler's negro servants. Stockton, members of the gun crew, and some of the other spectators were injured by fragments of the gun or by the powder flames. Newspapers of the time announced the explosion with the proper amount of lurid description and consternation. Beneath a headline "MOST AWFUL AND MOST LAMENTABLE CATASTROPHE," for example, the *National Intelligencer* of Washington stated the following day, "In the whole course of our lives it has never fallen our lot to announce to our readers a more shocking calamity." The victims, with the exception of the President's servant, lay in the East

Room of the White House. Both military services ordered an appropriate display of honors for the dead. On March 2 funeral services were held at the White House for all except the Negro and Maxey; the latter was buried after a family service.

During the period of building and pre-explosion displays, Stockton's once extreme enthusiasm for "the one man he had hunted the world over to find, who could build a complete ship" had perceptibly cooled. Ericsson became increasingly annoyed by these slights. It had been agreed that he would accompany the *Princeton* to Washington. "He proceeded accordingly to the foot of Wall Street at the appointed time, expecting to be taken aboard there, but the vessel carrying his fortunes, not less than those of Stockton, steamed by without stopping for him."

Investigation of the explosion quickly followed. Faced with the prospect of a court of inquiry, Captain Stockton called upon Ericsson to testify in his support in Washington. "If he was not disposed to share the credit of his success with him, he was quite ready to give him full measure of responsibility for failure." Ericsson replied that Stockton had the gun's plans and knowledge of its operation of February 28 in his possession; Ericsson could personally add nothing. He offered to investigate at the New York foundry where the "Peacemaker" had been finished. Pratt claims that Ericsson "had all along maintained the wrought-gun was built on a bad principle," but the gun was built along the lines of the "Oregon," and there is no other indication of technical disapproval. Ericsson seems to have been a man of deep sensitivity and a rather quick temper; the snubs of Stockton and lack of proper payment for his services were sufficient to justify his behavior. Captain Stockton, accustomed to the obedience expected by a man of power, was greatly angered by this refusal.

The court of inquiry dismissed the incident as an accident. Stockton, however, remained bitter toward Ericsson. In March when Ericsson submitted a bill of $15,080 for his services and patents, Stockton advised the Secretary, "I cannot approve of his bill; it is direct violation of our agreement as far as it is to be considered a legal claim upon the Department." From this time on Ericsson was called "a mechanic of some skill" or an "ingenious but presumptuous mechanic." The degree of Stockton's responsibility for the non-payment of Ericsson's claim and his motivation may be judged from his remark to Sargent: "If Ericsson had not been a damned coward, there would have been no trouble about his getting his money for the vessel." Contention over the unpaid claim continued. In 1857 the United States Court of Claims approved a payment of $13,930, but although Congress recognized the obligation, no payment was ever made. Stockton's biography makes no reference to the incident or, indeed, to Ericsson. The break had been final.

The *Princeton* remained in service until 1849, performing well during the Mexican War and was subsequently sent to the Mediterranean. Her influence upon European naval thinking was heavy; both the British and French designed steamers along similar lines. In 1848 she was condemned as rotten and broken up at the Boston Navy Yard. Stockton, through his biographer, later claimed that this was ordered by "the blundering incapables who controlled the Bureau of Construction" as revenge for the prestige he had gained from her building.

As with the *Fulton I* the United States failed to maintain its initial supremacy. Such isolated flurries of foresight could not by themselves offset the slower but persistent progress of the British. Treatment comparable to that given Ericsson could hardly be expected to attract the best available naval designers. There was, likewise, much jealousy within the Navy Department, a situation unlikely to produce consistent policies or effective planning. Within twenty years Ericsson won rather belated recognition with his *Monitor*. Although destroyed, the *Princeton* had served a valuable function in the history of naval design. In subsequent ships Ericsson's devices were incorporated and improved, becoming with time standard equipment. By any reasonable standard of judgment, this first screw warship had not been a failure.

"THE WELDING JOURNAL"

EFFECT OF COLD WORK ON THE MECHANICAL PROPERTIES OF PRESSURE VESSEL STEELS

ACKNOWLEDGEMENT

W. T. Lankford, of the United States Steel Corporation, is the author of this paper. It was published in the Welding Research Supplement of the April, 1956, edition of "The Welding Journal."

INTRODUCTION

IN THE MANUFACTURE of pressure vessels, cold-forming operations are used extensively in shaping initially flat plate material into desired vessel contours. The resulting plastic deformation plays an important role in establishing the mechanical properties of the material in the completed vessel. Local plastic deformation occurring at points of high stress concentration in a vessel when subjected to service loads may also result in significant changes in properties. It is the purpose of this interpretive report to review and appraise the present state of knowledge regarding the effects of cold work on the mechanical properties of steels, and to indicate areas where further research is needed. Emphasis has been placed wherever possible on data pertaining specifically to those carbon and constructional alloy steels that can be utilized in pressure vessel construction. Data on similar grades of carbon and constructional alloy steels are also presented, however, in order to provide a more general background of information.

If the practical significance of the effects of cold work on the properties of steel is to be appraised properly, it is essential at the outset that the inherently unstable nature of cold-worked steels be clearly recognized. While cold work, *per se*, produces pronounced changes in mechanical properties, further changes in the cold-worked material that result from secondary effects may also be quite significant. In general, the properties existing immediately following a cold-forming operation will have been modified, in varying degrees, by the time the material is placed in service and may continue to change during service. The nature and extent of the changes in properties that actually occur will depend on the type of steel involved as well as on the specific thermal history experienced by the cold-formed material during subsequent fabrication operations.

As has been discussed in another Materials Division interpretive report,[1] many steels that have been plastically deformed are subject to the phenomenon known as strain aging and undergo progressive changes in properties as a result of such aging. While strain aging can proceed at atmospheric temperatures, it is greatly accelerated even at moderately elevated temperatures. At still higher temperatures, the processes of recovery and recrystallization may become operative, thus providing still another source of modification of the properties of a cold-worked steel. Cold working, therefore, can in a sense be regarded as "conditioning" the material for the development of the properties that exist as the material is placed in service.

Since it is obviously important to understand all of the stages in the development of the final properties, the changes produced by cold work as such, as well as changes induced by subsequent fabrication operations and by exposure to service temperatures, will be considered in the following discussion. Strain aging will not be discussed in detail, however, inasmuch as it has been treated in another report.[1]

In most of the experimental work that has been carried out for the purpose of evaluating the effects of cold work on properties, methods of straining have been employed that produce essentially uniform strains through the cross section of the specimen. The objective of such experiments has been primarily to establish trends and to reveal differences in materials

under closely controlled conditions of cold working. The problem of relating results of tests on uniformly strained specimens to the property changes that would occur in plates formed into pressure vessel components, in which the strains would generally not be uniform, has received relatively little attention. Emphasis has been placed in this report, therefore, on outlining basic trends and indicating the nature of the changes in properties resulting from cold work. As a rough guide in considering the effects of various amounts of cold work, it may be noted that forming of 1-in.-thick plate into cylinders ranging in diameter from 20 in. to 120 in. results in outer fiber strains ranging from about 5% for a diam. of 20 in. to about 0.8% for a diam. of 120 in. It is also of interest to note that Paragraph UCS-56 (a) (5) of Section VIII of the ASME Boiler and Pressure Vessel Code limits the thickness, and thereby the strain, permissible without stress relieving for a given diameter of vessel. The maximum thickness is given by $(D + 50)/120$ in. where D is the ID of the vessel, or 20 in., whichever is greater. It happens that the greatest strain permitted on the basis of this formula is slightly less than 3%, corresponding to a D value of 20 in.

Before the various changes in properties resulting from cold work are considered in detail, the following circumstances may be cited to indicate the various conditions that can lead to changes in the mechanical properties of cold-worked steels:

1. Exposure to atmospheric temperatures
2. Exposure to preheating or post-heating in connection with welding
3. Exposure to the heat of welding
4. Exposure to the heat of stress-relief annealing

It is readily apparent that the thermal conditions that can be encountered, as well as the volumes of material affected thereby, are subject to wide variation. Consequently, wide variations in the properties of a previously cold-formed steel can be expected in a completed pressure vessel.

EFFECT OF COLD WORK ON STRENGTH PROPERTIES

When steel is plastically deformed at ordinary or moderately elevated temperatures, its resistance to continued deformation progressively increases. This increase in strength or flow resistance is known as "strain hardening" or "work hardening" and is one of the most important effects of cold working. Strain hardening can be described most simply by considering the so-called "true" stress-strain curve determined in a uniaxial tension test. In the true stress-strain relationship, stress is based on the actual area of the specimen at any instant, rather than on the original area, i.e., stress is corrected for the changing cross section of the specimen. Likewise, strain is based on the instantaneous gage length of the specimen, rather than on the original gage length. With stress and strain defined in this manner, the stress-strain relationship appears as shown in Fig. 1. It is evident that the stress required to cause further deformation increases continuously as the strain increases. The

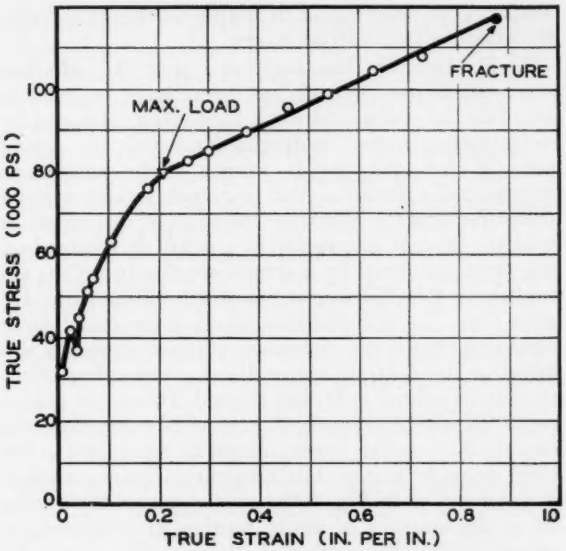

Figure 1. True stress-strain curve for annealed 0.19% C, 0.85% Mn steel (MacGregor[2]).

slope of the stress-strain curve at any point is a measure of the rate of work hardening, i.e., the rate at which the stress required to produce further deformation is increasing. It can be seen that the rate of work hardening decreases with increasing strain. This behavior results in the occurrence of a maximum load and the familiar phenomenon of necking down. At low strains the rate of work hardening is sufficiently high that, even though the cross-sectional area of the specimen is decreasing, the specimen can carry a larger load as the strain increases. Finally, however, the rate of work hardening decreases to such an extent that the loss of cross section is no longer compensated and the net load-carrying capacity of the specimen decreases.

When plastic deformation occurs under complex stress conditions, special stress and strain functions sometimes referred to as "effective stress" and "effective strain" can be employed to describe work hardening. These functions, which take into account all the principal stresses and strains, were developed on the basis that a single stress-strain curve should describe the plastic deformation of a given material under any state of stress. Considerable experimental evidence supports the validity of this theory for isotropic materials.[3] Similar relationships have been developed[4] for materials having certain types of simply defined directionality, but the introduction of parameters to correct for directionality is required. Hot-rolled, annealed, normalized, or quenched-and-tempered plate steels can be expected to be sufficiently isotropic that the strain-hardening characteristics can be described by the unmodified effective stress-strain relationship. It should be noted that the constants involved in the definitions of effective stress and effective strain can be chosen so that the stress-

strain curve determined in simple tension is actually the effective stress-strain curve.

L. R. Jackson[5] has suggested that the effective stress-strain relationship can sometimes be used to estimate the amount of work hardening produced by deformation under conditions for which the actual state of stress may not be known. If the strains are substantially uniform, the principal strains can be measured and the effective strain can be computed. A true stress-strain curve can be quickly determined on the virgin material by a simple tension test, thus establishing the effective stress-strain relationship. By then referring the effective strain determined after straining under the unknown state of stress to the effective stress-strain curve, the corresponding effective stress value can be ascertained. This value represents the effective stress that would be required for further flow, or can be considered as equivalent to the yield stress for material that has the measured amount of prior strain. In Fig. 2, the application of this method to the analysis of strain hardening produced by reduction by cold rolling is illustrated.[2,5] It can be seen that points determined by measuring yield stresses in simple tension after various amounts of cold rolling lie along the same curve established by straining entirely in tension. For large and substantially uniform strains, therefore, it appears that work-hardening effects can be predicted from a knowledge of the principal strains and the flow curve determined in simple tension.

It is of interest to note in Fig. 2 that the stress-strain values lie on a straight line on a double logarithmic plot. For most ferritic steels, it has been found that the true stress-strain curve can be approximated very closely, at least up to maximum load, by the empirical relationship, stress $= k \times$ strain^n where k and n are material constants usually referred to as the strength coefficient and the strain-hardening exponent, respectively.[6] These two parameters provide a convenient and widely used method for describing the stress-strain curve. The strain-hardening exponent n is intimately related to the amount of uniform elongation that the material is capable of undergoing, i.e., elongation prior to necking down. Larger n values correspond to larger uniform elongations.

It has been shown that for large uniform strains, the analysis of the response of the material with respect to strain hardening is rather straightforward. For small amounts of prior strain, however, the behavior of most steels is unfortunately not so simple. When in the hot-rolled, normalized, or annealed condition, most ferritic steels of the types used in pressure-vessel construction exhibit an abrupt type of yielding which is quite different from the gradual type of yielding observed in nonferrous metals and austenitic steels. Although the abrupt yielding behavior is very familiar, its general features will be briefly reviewed. The stress at which strain rapidly increases with no further increase in stress is known as the yield point. In some instances a drop in load

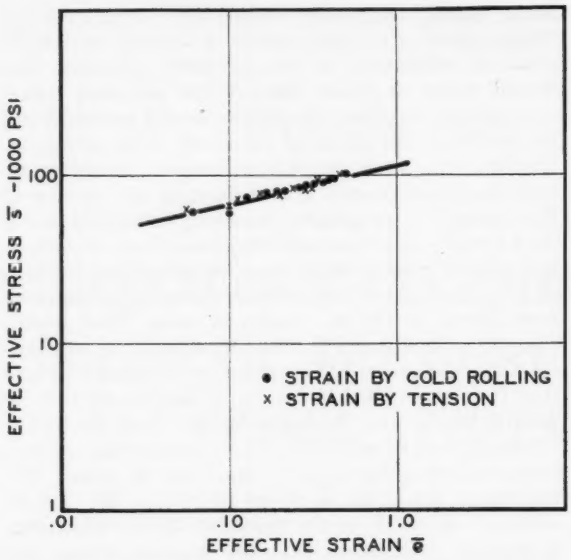

Figure 2. Comparison of work hardening by cold rolling and by simple tension for annealed 0.19% C, 0.85% Mn steel (Jackson[5]).

occurs upon initial yielding, and flow continues at a somewhat lower load. The stress at which yielding first begins is then usually referred to as the upper yield point, while the lower stress level at which flow continues is known as the lower yield point. The amount of elongation occurring before the stress-strain curve begins to rise uniformly is known as the yield-point elongation. The yield-point elongation may vary from a slightly perceptible jog in the stress-strain curve for steels quenched and tempered to high hardness levels to values of elongation approaching 10% for box-annealed deep-drawing steels. The yield-point elongation for structural carbon-steel plate materials is usually in the neighborhood of 1 to 2%. During the yield-point elongation, the specimen does not strain uniformly, but rather by the progressive formation of localized strain bands, known as Lüder's lines or bands. Only one or a very few Lüder's bands form on initial yielding, and the remainder of the specimen remains unyielded. As straining proceeds, Lüder's lines continue to form and propagate until the end of the yield-point elongation range is reached.

Steel that has been cold worked prior to testing may exhibit gradual yielding rather than a definite yield point, and under certain circumstances may yield at a somewhat lower stress than that observed prior to cold working. The effect of cold work introduced by bending and straightening of ½-in.-thick standard ASTM plate specimens of a semikilled carbon steel (0.23 C, 0.40 Mn)[7] is illustrated in Fig. 3. The specimens were bent to the indicated permanent deflections by a uniform bending moment acting over a 10-in. span and were then straightened by reverse bending. The outer fiber strains in the bent

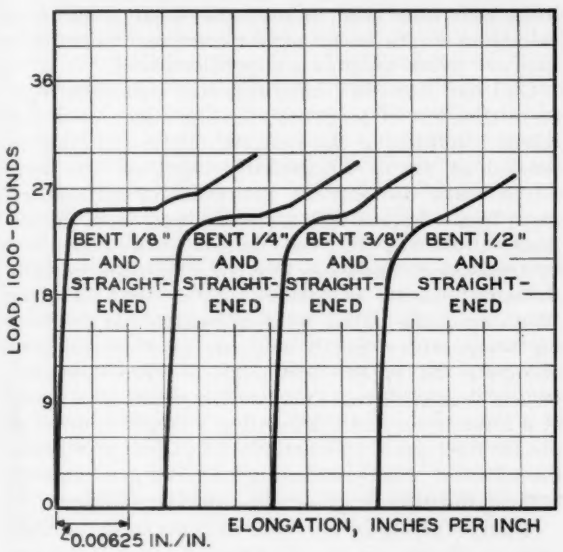

Figure 3. Effect of bending and straightening on the initial yielding characteristics of ½-in. thick carbon-steel plate material.

conditions amounted to approximately 0.38% for the ⅛-in. bend, 0.63% for the ¼-in. bend, 0.87% for the ⅜-in. bend, and about 1.11% for the ½-in. bend. It can be seen that after the bend of ⅜-in. and straightening the yield point disappeared. The stress of 0.2% offset dropped from 34,600 psi for the hot-rolled material to 31,300 psi for that bent ½ in. and straightened. The yield-point elongation for the hot-rolled material was about 1.5%. It appears likely that residual stresses produced by the flexing operation are responsible for lower initial yield stresses.

Osborn, Scotchbrook, Stout, and Johnston[8] conducted an extensive series of tests on 1¼-in.thick plates of rimmed A-285 (formerly A-70) and silicon-aluminum killed A-201 steels to determine the effect of cold work on the tensile properties. Axial tensile strains of 1, 5, and 10% were applied, as well as an axial compressive strain of 1%. In addition, some specimens were strained 1% in tension in the direction perpendicular to the direction of subsequent testing. Tests were conducted after a standard elapsed time of five days with the objective of immunizing differences arising from aging. The present discussion of the results will be confined to tests of longitudinal specimens, i.e., those parallel to the rolling direction of the plate. The larger tensile prestrains raised the yield points of both materials very markedly. The prestrain of 5% resulted in an increase of about 27,000 psi, while the prestrain of 10% produced an increase of about 37,000 psi. A tensile strain of 1% in the rolling direction had practically no effect on the yield point of the A-201 steel but raised the yield point of the A-285 steel about 8,000 psi. The compressive prestrain or the transverse tensile prestrain tended to lower the stress required to produce yielding in tension. This phenomenon, wherein a prior strain in one direction lowers the stress required to produce yielding under subsequent loading in the opposite direction, is known as the Bauschinger effect.

It can be seen, therefore, that no simple rules can be advanced for predicting the quantitative effects of small amounts of prior strain on initial yielding. The response varies with the manner in which the prior strain is produced, and also undoubtedly varies considerably with the extent of the yield-point elongation present in the original material. Qualitatively, it can be said that a tensile strain less than the yield-point elongation will have little effect on the lower yield point but may eliminate the upper yield point. If a prior tensile strain is greater than the yield-point elongation, the yield stress should be higher than that of the virgin material, and abrupt yielding may be replaced by gradual yielding. Small prior strains produced by compression, or by tension applied in a direction perpendicular to the direction of testing, tend to lower slightly the stress required for yielding (the Bauschinger effect). If compressive prestraining is continued to sufficiently high values, the tensile yield stress will rise above that of the original material as a result of strain hardening.[15] If the prior strain is produced by bending, so that residual stresses are set up, relatively small prior strains may result in gradual yielding and a lowering of the apparent stress at which yielding is initiated.

Stout and co-workers[8] state that with the exception of the 1% prestrain on the A-201 steel, all plastic prestrains raised the nominal maximum stress (tensile strength) in the tension test. The magnitude of the effect increased with increasing prestrain and amounted to about 8,000 psi for prestrain of 10%. It appears that a large part of the reported increase in tensile strength can be accounted for by the fact that the tensile strength of the cold-worked material is computed on the basis of the new area after straining. Thus, an increase in tensile strength would be reported even though the maximum loads for specimens with and without prior cold work were identical. Strain aging between prestraining and final testing may have contributed slightly to the observed increases in tensile strength.

EFFECT OF COLD WORK ON DUCTILITY AND FRACTURE STRESS IN THE TENSION TEST

A. *Ductility.* Extensive investigations of the effects of prior straining on the ductility of steels in tension tests have been carried out. One type of experiment frequently conducted involves prestraining at a temperature above the range of temperature in which the transition from ductile to brittle behavior occurs, and then measuring the remaining ductility at some lower temperature. The simplest type of behavior can be illustrated as shown in Fig. 4*a*. The strain to fracture at Temperature 2 after prior straining at Temperature 1 decreases linearly with in-

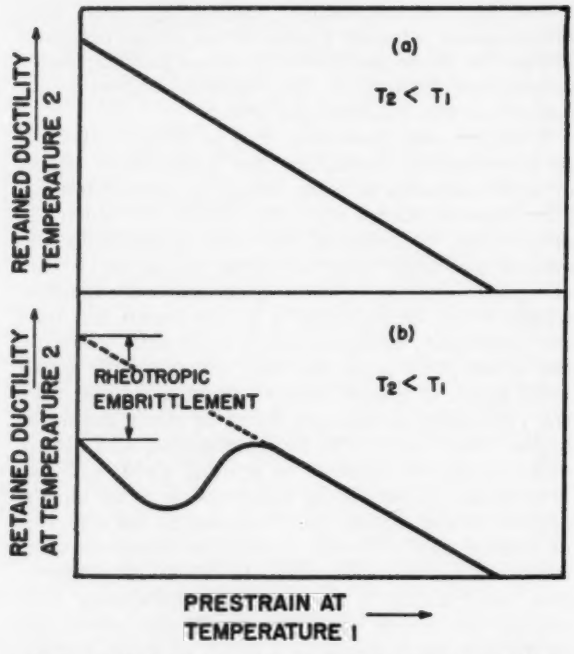

Figure 4. Schematic illustration of rheotropic embrittlement.

creasing prior strain. For example, if a strain is applied at Temperature 1 corresponding to 75% of the fracture strain at that temperature, then the additional strain at Temperature 2 before fracture will be 25% of the ductility that would have been observed at that temperature if there had been no prior strain at Temperature 1.

Under certain circumstances, however, quite complex effects resulting in the type of behavior illustrated in Fig. 4*b* may occur. For small prestrains, the ductility at Temperature 2 drops rather rapidly, but at somewhat higher prestrains begins to rise, passes through a maximum that may be considerably in excess of the value for no prestrain, and then decreases in a regular manner. The relative magnitude of the changes in ductility that are observed as the prestrain is increased may vary considerably, and in some instances the initial drop in ductility at low prestrains may be hardly detectable. Since the deficiency of ductility at the lower prestrains can be partially eliminated by prior plastic flow, the behavior has been termed "rheotropic" embrittlement by Baldwin and co-workers.[9] While this type of behavior had been observed by other investigators,[10] the phenomenon has been subjected to extensive systematic study by Baldwin. An understanding of the mechanism of rheotropic effects on low-temperature behavior should be of value in developing a better understanding of the general problem of low-temperature embrittlement of ferritic steels. The practical implications of rheotropic embrittlement, however, are not as yet clear. Only a limited amount of work has been reported in which notched specimens have been used, and whether small amounts of cold work might under some circumstances actually improve notch toughness is problematical.

Geil and Carwile[11] have reported that rheotropic embrittlement of ingot iron is dependent upon the initial condition of the material. Prior straining in tension at room temperature improved the low-temperature ductility of hot-rolled or normalized ingot iron, whereas with annealed ingot iron, the opposite effect was observed. Recent work carried out by Gensamer[12] indicates that the rheotropic embrittlement behavior is related to the effect of prior strain upon the initial yielding behavior at the testing temperature. Small amounts of prestrain may eliminate the upper yield point at the subsequent testing temperatures, thus causing yielding to occur at a lower stress and permitting a larger amount of plastic flow prior to fracture. At larger prestrains, the effect of strain hardening becomes predominant and the ductility decreases in a regular manner.

Another aspect of the effect of prior strain on ductility is illustrated by Bridgman's work on prior straining under high hydrostatic pressure.[13] Bridgman found that if a specimen was elongated in the presence of a high hydrostatic pressure, the ductility was very much greater than at atmospheric pressure. Furthermore, after prestraining under hydrostatic pressure, considerable ductility remained at atmospheric pressure even though the prior strain exceeded the original fracture strain at atmospheric pressure. Sachs[10] also discusses the different effects on ductility obtained by prestraining in tension, in wire drawing, or in extrusion. The compressive stresses prevailing in the latter methods of deformation result in greater remaining ductility after a given amount of extension. These observations are mentioned only as a matter of general interest, inasmuch as it is believed that the variations in hydrostatic compression that would be encountered in plate-forming operations would be too small to result in significant effects of this type. Under some conditions, small amounts of prior compressive strain may tend to lower ductility because of a tendency to lower the fracture stress, as discussed in the following section.

B. *Fracture Stress.* In general, the breaking stress or fracture stress is affected by prior strain in much the same manner as yield stress. Fracture stress is quite difficult to study because it is a function of so many different variables. Perhaps the most straightforward studies of the effect of cold work on fracture stress have been those in which a prior strain is applied at room temperature and the final testing carried out at a low temperature at which very little ductility remains. Thus, strain at the low temperature does not tend to mask the effects of the prior strain at a higher temperature. It has been observed that under these conditions, increasing amounts of prior tensile strain result in an increasing fracture stress.[14] For prior straining in compression, McAdam has shown that the fracture stress at first decreases

and then increases continuously with increasing compressive strain.[15] With regard to the effect of prior compressive straining, McAdam states: "The effect on the tensile fracture stress is similar to the effect on the tensile flow stress. The effect is the resultant of two factors, namely, a shift of the elastic range and a work-hardening effect." The shift of the elastic range referred to is the Bauschinger effect, described previously in this report. This observation is in accord with Zener's hypothesis,[16] also held by many others, that fracture in metals is always preceded by plastic flow at least on a microscopic scale, even though there may be very little, if any, outward evidence of ductility. Furthermore, it is presumed that so-called "brittle" fractures of steel are nucleated by stress concentrations resulting from the first microscopic traces of plastic flow. According to this view, therefore, prior straining in compression would be expected to at first lower the fracture stress, because plastic flow would be initiated at a lower stress as a result of the Bauschinger effect.

EFFECT OF COLD WORK ON NOTCH TOUGHNESS

It is generally recognized that cold working impairs the ability of ferritic steels to resist the initiation of brittle fracture. In actual practice, the effects of strain aging are superimposed on the effects of the cold work. While the final toughness is of primary interest from the point of view of the suitability of the material for service, it is important to know the relative contributions of straining and of aging to the impairment of toughness, if steps are to be taken to design steels of improved overall resistance to the effects of cold work.

A number of different procedures have been employed in evaluating the effects of cold work on toughness. Not only has a variety of methods of introducing cold work into the material been employed, but also numerous types of test specimens have been employed. The significance of notch toughness tests and methods of evaluation of results of various tests have been discussed at length elsewhere[17-19, 37] and will not be reviewed in this report. It is now generally recognized that for the most information and least ambiguous results, tests to evaluate the effects of cold work on toughness must be conducted over a range of temperatures so that the transition temperatures for each condition to be studied can be determined. Tests conducted only at room temperature have been subject to misinterpretation in the past, even though a range of degrees of cold work was used. Unless otherwise indicated, attention will be directed herein primarily at the change in the so-called "ductility" transition temperature, which is considered to be intimately associated with crack initiation. It has been pointed out elsewhere[19] that the fracture transition temperature, or transition temperature based on fracture appearance, is usually not greatly affected by cold work, especially if the ductility transition temperature for the test under consideration is well below the fracture transition temperature for the virgin material. If the ductility transition temperature is about the same as the fracture transition temperature, then increasing amounts of cold work will tend to increase both transition temperatures at the same rate.

Straining in tension has been the most commonly employed method of introducing cold work for the purpose of evaluating the effects of cold work on notch toughness. This procedure has the advantage that a relatively large area of material can be strained at one time, thus providing a number of specimens with only one straining operation. Straining has also been carried out prior to testing for notch toughness by reduction as a result of rolling and by axial compression. The latter methods have the advantage that, with the exception of notching, individual impact specimens can be completely machined to final dimensions prior to straining. In this manner, the time interval between straining and testing can be kept to a minimum. Another method of straining involves the drawing of a tapered bar through a die, thus producing a continuous variation of cold work along the bar, the range of strain being determined by the taper.

Stout and co-workers[8] studied the effects of cold work on the notch toughness of 1¼-in. thick plate material of A-285 steel and A-201 steel (the same two heats previously mentioned). The Charpy V-notch impact test and the Lehigh slow notch-bend test were used. Transition temperatures were evaluated on the basis of energy absorption, fracture appearance, and lateral contraction measured $^{1}/_{32}$ in. below the base of the notch. For the evaluations of transition temperature based on energy absorption, the criterion used was the temperature at which the energy value was midway between minimum and maximum values. Similarly, for the evaluation based on lateral contraction, the criterion selected was the temperature at which the value of lateral contraction was midway between the minimum and maximum values. The fracture-appearance transition temperature was selected as the temperature corresponding to 50% fibrous fracture. A standard elapsed time of seven days after final treatment was employed for the Lehigh slow notch-bend test, while a period of ten days was used for the Charpy V-notch impact tests.

The increases in transition temperature resulting from the various straining treatments are summarized in Table 1. On the basis of energy absorption in the Charpy V-notch impact test, the A-285 steel exhibited a somewhat greater shift than did the A-201 steel. It was also observed that while the transition temperature of the A-201 steel was shifted progressively to higher temperatures with increasing amounts of tensile strain, that of the A-285 steel was shifted almost as much by 1% tensile strain as by 10%. The shifts observed after 10% strain were about 50° F for the A-201 steel and about 75° F for the A-285 steel. If a criterion of lateral contraction is used, the data appear somewhat inconsistent, but the shifts in transition temperature resulting

from 5 and from 10% cold work were not greatly different for the two steels. In the Lehigh slow notch-bend test, the A-285 steel exhibited a considerably greater shift in transition temperature after 5% strain than did the A-201 steel, but after 10% strain the shifts were very similar for the two steels, amounting to about 89–90°F. Lehigh slow notch-bend tests were also conducted on ⅝-in.-thick plate material that had been strained 20% in tension from each of these two heats.[20] Again the two steels exhibited very similar shifts of transition temperature. An increase of about 81°F was observed for the A-201 steel, while that for the A-285 was about 89°F.

TABLE 1

Effects of Cold Work on Transition Temperatures of A-285 and A-201 Steels (1¼-In.Thick Plates) in Charpy V-Notch Impact Tests and Lehigh Slow Notch-Bend Tests (Stout, et al)

	Increase in transition temperature (° F)			
	A-201		A-285	
Strain	Energy	Lateral Contraction	Energy	Lateral Contraction
Charpy V-notch impact test				
1% Compression ..	32	7	30	18
1% Tension	28	2	63	48
5% Tension	38	44	66	57
10% Tension	48	50	77	32
Lehigh slow notch-bend test				
1% Compression		45	..	43
1% Tension		27	..	10
5% Tension		38	..	90
10% Tension		81	..	90

Compressive strains of 1% caused a shift in transition temperature in the Lehigh slow notch-bend test of about 45° F for both steels as compared with shifts resulting from 1% tensile strain of about 10° for the A-285 steel and 25° for the A-201 steel. In the Charpy V-notch impact test, on the other hand, the two methods of straining produced about the same shift in transition temperature for the A-201 steel, but tensile straining produced a larger shift than did compressive straining for the A-285 steel. Some of the seeming inconsistencies in the results for the material strained 1% may possibly be attributable to the difficulty of obtaining uniform deformation at such a low average strain level.

With regard to the over-all interpretation of the results, it is interesting to note that in the final summary of the five-year program at Lehigh University, Tör and Stout[21] state: "One simplification can be made at the outset of this discussion. The aluminum-killed A-201 and the rimmed A-285 steel responded to all of the simulated fabrication operations in essentially the same manner. The notch toughness of the A-285 was inherently lower than that of the A-201, but prestraining or welding or heat treatment altered both steels in the same direction and to about the same extent."

TABLE 2

Increases in Charpy Keyhole-Notch Transition Temperatures Resulting from Cold Working (in Tension) of Several Ship-Plate Steels (Klier, Wagner and Gensamer)

	Increase in Transition Temperature (° F)		
Steel*	2% Strain	5% Strain	10% Strain
A	40	55	60
Br	20	45	50
Bn	20	30	55
C	40	55	70
Dr	20	45	75
Dn	— 5	25	40
E	45	40	55
H	—10	25	40

* Designations used by Klier, Wagner and Gensamer.

Klier, Wagner, and Gensamer[22] reported results of tests on a series of ship-plate steels in which the effects of axial tensile strains of 2, 5 and 10% on transition temperatures in the Charpy keyhole-notch impact test were determined. Average curves were drawn through the data and transition temperatures were selected at 25 and 50% of maximum energy absorption. In the following discussion, the values selected at 25% of maximum energy will be used inasmuch as this criterion is believed to correspond more closely than those selected at 50% to the ductility transition temperature as usually defined for the Charpy keyhole-notch impact test. The results are summarized in Table 2. For 2% strain, the reported shifts in transition temperature ranged from —10 to 45° F. (The two values of negative-shift reported are not considered sufficiently great to be significant.) For 5% strain the shifts ranged from 25 to 55° F, and for 10% strain from 40 to 75° F. No consistent trends with steelmaking practice were discernible. One steel with higher than normal nitrogen (0.010%) exhibited a shift that was on the high side of the observed range; on the other hand, a similar steel with normal nitrogen exhibited just as large a shift in transition temperature. When it is considered that an individual transition temperature determination based on the number of specimens employed by Klier, Wagner, and Gensamer is probably uncertain to about ±20° F, at least part of the variation among results for the various steels can be attributed to experimental scatter. The time interval between straining and testing in the above tests was about one month. In order to explore the possibility of variations caused by room-temperature aging, another series of tests in which straining was performed by axial compression was conducted on two of the steels. The specimens were finish-machined, with the expection of the notching, to dimensions selected so that the dimensions after straining would be within standard tolerances. This procedure permitted a transition curve to be determined within one hour after straining. Tests were conducted after a series of aging times ranging up to four weeks for

two of the ship-plate project steels. While the data are somewhat inconsistent, there is an indication that for one of the steels an increase of 15 to 20° F in transition temperature accompanied the increase in aging time from one hour to four weeks. Inasmuch as no trend was found for the other steel tested, however, the results must be regarded as somewhat inconclusive. It would appear that for the particular steels tested by Klier, Wagner and Gensamer and for the number of tests used in establishing a transition curve, the effect of aging in shifting the transition temperature was no more than 15 to 20° F and was probably within the accuracy of the experiment. For the most precise separation of the effects of cold working and of strain aging following cold working, the time interval between straining and testing should be kept to a minimum and carefully controlled for the specimens that are not deliberately strain aged.

Epstein[23] reported a series of tests on ship-plate steels in which the effects of straining in compression on the transition temperature in the Charpy keyhole-notch impact test were measured. The temperature corresponding to 20 ft.-lb. energy absorption was used as the criterion of transition temperature. Epstein tested material from several heats each of American Bureau of Shipping Classes A, B and C hull-plate steel. The carbon and manganese contents are not specified for Class A steel, but usually average about 0.23% C and 0.45% Mn. This steel is used in plates up to ½ in. in thickness. In Class B steel, which is used in plates over ½ in. and up to 1 in. thick, the carbon content is limited to 0.23% max and the manganese content is from 0.60 to 0.90%. Class C steel is used in plates over 1 in. in thickness. It contains a maximum of 0.25% carbon, 0.60 to 0.90% manganese, and 0.15 to 0.30% silicon and is made by fully aluminum-killed, fine-grain practice. For the purpose of the tests conducted by Epstein, commercial plates of all three grades were rolled to ¾-in. thickness. No information is given regarding the time interval between straining and testing.

Epstein's results are summarized in Table 3. It can be seen that each grade exhibited about the same shift in transition temperature as a result of straining. The average increases in transition temperature produced by 5% compression were 58, 53 and 52° F for Classes A, B and C, respectively. The average shifts produced by 10% compression were 65, 62 and 63° F for Classes A, B and C, respectively. Thus, on the basis of these data, there do not appear to be significant differences in the response of these three grades of steel to cold work. It should be noted, of course, that initial transition temperatures prior to cold working are significantly different for the three types of steel as tested by Epstein. The average transition temperatures of the material before straining as reported by Epstein are +26, −1 and −39° F for Classes A, B and C, respectively. Since the shifts in transition temperature produced by cold work were almost the same for all three steels, the differences among the transition temperatures after cold working will be the same as before cold working.

Markus and Armiento[24] investigated the effect of cold work on the notch toughness of a 1030 cartridge case steel, which contained 0.27% C and 0.64% Mn and was aluminum-killed. Cold rolling was used as a method of straining, with the time interval between straining and testing being held constant at 30 days. The material was tested in the four following conditions that were produced by variations in heat treatment: (1) spheroidized, fine-grained; (2) spheroidized, coarse-grained; (3) pearlitic, fine-grained; and (4) pearlitic, coarse-grained. The test specimen employed was a Charpy-type impact test specimen with a notch root equivalent to that of the keyhole-notch specimen but with the notch machined by a U-shaped milling cutter rather than by drilling and slotting. Transition temperatures were selected at the highest temperature at which a brittle fracture (low-energy absorption) was obtained. Usually groups of five specimens were broken at 5° F temperature intervals in the vicinity of the transition temperature. Curves illustrating the effect of various amounts of cold work on the transition temperatures selected in the indicated manner are shown in Fig. 5. It can be seen that the transition temperatures increase more rapidly at low strains. For three of the conditions, the curves very nearly parallel one another. The fine-grained, spheroidized material, however, shows somewhat smaller increases in transition temperature with increasing cold work than do the other three materials. It is interesting to note that at 10% strain the average increase in transition temperature for these materials amounts to slightly more than 50° F, agreeing well with values observed by Klier, Wagner and Gensamer as well as by Epstein for different methods of straining.

TABLE 3

Effects of Cold Work (by Compression) on the Transition Temperatures in Charpy Keyhole-Notch Impact Tests of Plates of ABS Classes A, B and C Steel (Epstein)*

Steel	Number of Plates Tested	Increase in Transition Temperature (° F) after 5% Strain		Increase in Transition Temperature (° F) after 10% Strain	
		Range	Average	Range	Average
A	5	53–66	58		
	4			54–70	65
B	1		53		
	3			48–72	62
C	2	52–52	52		
	2			56–70	63

* All plates rolled to ¾-in. thickness for comparative purposes.

On the basis of the foregoing analysis, it appears that, for open-hearth steels having composition in the range of 0.15 to 0.30% C and 0.40 to 0.90% Mn, a strain of about 10% results in an increase of tran-

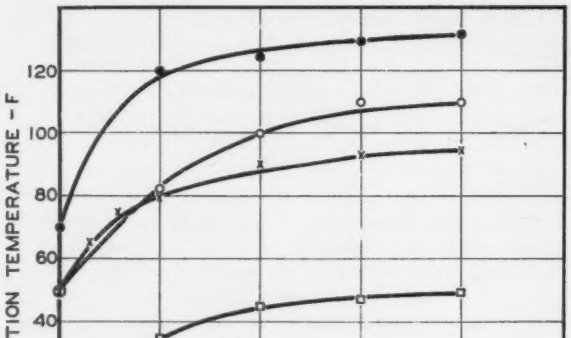

Figure 5. Effect of cold work on the transition temperature of a 1030 cartridge-case steel in the Charpy keyhole-notch impact test (Markus and Armiento[24]).

sition temperature in the Charpy keyhole-notch test of about 50 to 70° F.

Limited data indicate that capped or semikilled bessemer steel may undergo a much greater increase in transition temperature when cold worked, because of the combination of high phosphorus and high nitrogen. In one experiment,[25] cold rolling 10% increased the transition temperature of a semikilled bessemer steel containing 0.15% C and 0.45% Mn by about 150° F in the Charpy keyhole-notch impact test. Because of the high nitrogen content, this steel may have aged appreciably in even a short period at room temperature after straining and before testing.

Limited information suggests that steels having a tempered martensitic microstructure may be less susceptible than pearlitic steels to a decrease of notch toughness as a result of cold work. In tests of material from two heats of "T-1" steel, which is a low-carbon quenched-and-tempered alloy steel,[26] increases of 35 and 20° were observed after 10% strain produced by cold rolling.[27] Material from a ½-in.-thick plate of AISI 4815 (3½% Ni, 0.25% Mo) steel, that had been quenched and tempered, exhibited an increase of 28° F after similar straining, but an increase of about 100° F in the normalized and tempered condition.[28] Work currently in progress under the auspices of the Materials Division of PVRC on higher strength steels (at 50,000, 70,000 and 90,000 psi yield point levels) will add to the fund of information on the effects of cold work on notch toughness.

The methods of straining discussed up to this point have been of such a nature that the strains produced were essentially uniform throughout the specimen. Cold work introduced in actual forming operations on the other hand, is more likely to vary from point to point in a manner determined by the contour being formed and the method of forming. For example, in a cylindrical bend, the strains will vary from a tensile value on the convex side of the bend to a compressive value on the concave side. For a given plate thickness, the maximum values of strain depend on the radius of the bend, being larger for smaller radii. The question naturally arises as to what effect the type of cold work introduced in actual forming operations has on notch toughness. Only a limited amount of work aimed at clarification of this problem has been reported.

Stout and co-workers[20] studied the effects of cylindrical bending using a modified version of the Lehigh slow notched-bend test specimen. A cylindrical bend was introduced in the specimen in such a way that a tensile strain of 5% was obtained at a depth of 0.08 in. below the surface. This depth corresponded to the depth of the Izod notch which was machined after bending. The testing procedure was the same as for the Lehigh slow notch-bend test. Transition temperatures determined in this manner for the A-285 and A-201 steels, which were mentioned previously in connection with the Lehigh program, agreed within experimental error with values obtained using specimens axially strained 5% in tension.

The effects of spherical pressing were also studied in the Lehigh program.[20] For this purpose a special specimen and testing jig were developed. Circular plates ⅝-in.-thick and 16-in. in diam. of A-285 and A-201 steels were both cold pressed and hot pressed to a spherical radius of 16 in. A circular V-notch, 0.12 in. deep was machined at a radius of 2¼-in.

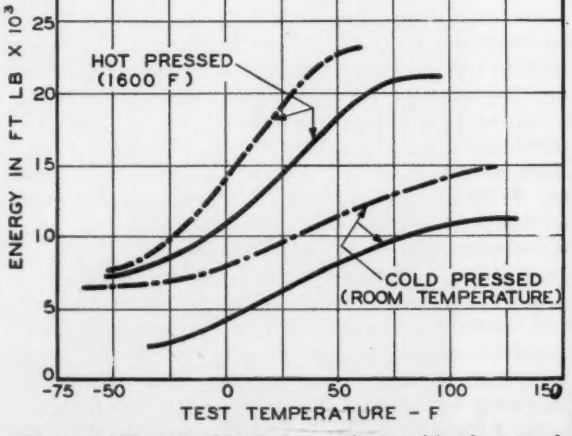

Figure 6. Effect of cold pressing on the transition from tough to brittle behavior of 16-in. radius spherical heads of A-285 and A-201 steels (Stout[20]).

after completion of the forming operation. During testing, the central portion of the specimen bounded by the notch was supported, and a load was applied around the periphery of the specimen so that the root of the notch was placed in tension. Total energy to fracture was recorded and used in constructing the transition curves shown in Fig. 6. It is clear that in this test cold pressing shifted the transition curves to higher temperatures, in addition to lowering the ability of the material to absorb energy at any particular temperature. Unfortunately, insufficient testing was conducted to permit correlation of results of this test with results of other tests conducted in the Lehigh program.

At this juncture, it should be pointed out that, although a great deal of attention has been directed toward the effects of strain aging on notch toughness, surprisingly little work has been carried out in an effort to evaluate the effects of prolonged aging at atmospheric temperatures. Although strain aging is not to be discussed at length in this report, it should again be indicated that the property changes discussed up to this point are essentially the effects of cold working alone, with at most a few days of aging at room or atmospheric temperatures. Most studies of the effect of aging on toughness have made use of elevated temperature aging treatments. While such experiments indicate the effects to be expected from heating at the selected temperatures, the effects that would result from prolonged atmospheric temperature aging are not necessarily revealed. Smith and Garofalo[29] studied the effect of aging at 75° F after straining 10% in tension for exposure times ranging from 1 hr to 25,000 hr. for three steels indicated in Table 4. A Charpy V-notch specimen of one-half standard width (parallel to notch axis) was used. Transition temperatures were selected at the 10 ft-lb level. For steels A and B, a shift of from 25-30° F was produced by an increase of aging time from 5 hr. to 25,000 hr. For steel C, the transition temperatures for the cold-worked and aged conditions were above room temperature and it is likely that aging occurred during testing. Aging was also carried out at 450° F for times up to 25,000 hr. In Table 4 the maximum shifts in transition temperature after aging at the two temperatures are indicated. In every instance, aging at 450° F. produced a much larger increase in transition temperature than did aging at 750° F. Furthermore, for steels A and B, the increase resulting from 5 hr. aging at 450°F was greater than the increase produced by 25,000 hr. at 75° F.

EFFECT OF PRIOR STRAIN ON THE PERFORMANCE OF WELDMENTS

When a weld is made on a cold-worked plate, the properties of the cold-worked base material will be altered throughout the zone in which the temperature is raised by the heat of welding. The change at any particular location will depend on the time-temperature cycle experienced by the material in that location. In much of the heated zone the notch toughness will be impaired as a result of strain aging. The changes so produced will contribute to the performance of the weldment as a whole in a manner depending on the extent of the changes and the volumes of metal affected. Stout and co-workers[30] conducted Lehigh slow notch-bend tests on a series of A-285 and A-201 steels that had been strained 5% in tension prior to welding. The results of tests on these specimens are compared in Fig. 7 with results of tests on welded but unstrained specimens. It can be seen that the transition temperature (based on percent lateral contraction) for material strained prior to welding was higher than for material unstrained prior to welding. Loss of toughness in cold-worked zones heated by welding contributed to an overall loss of toughness of the specimen as a whole. The increase in transition temperature so produced, however, was much less than that produced by welding alone, relative to the transition temperature of unwelded material.

EFFECTS OF HEATING COLD-WORKED MATERIAL

As mentioned earlier, cold-worked metals are not stable. The properties tend to change with time, the rate of change being faster the higher the temperature. Cold-worked ferritic steels tend to strain age at atmospheric and moderately elevated temperatures. As discussed in previous interpretive reports, strain aging tends to produce a further increase in strength and a further loss of ductility and toughness above and beyond that produced by cold work alone.

Another process, known as recrystallization, also tends to occur in all cold-worked metals.[31] The individual grains or crystals of a polycrystalline metal are distorted by cold work to an extent depending upon the nature and degree of cold working, and become

TABLE 4

Maximum Increase in Transition Temperature (Modified V-Notch Charpy Test) After Straining 10% in Tension and Aging at 75 or 450° F for Three Carbon Steels (Garofalo and Smith)

Steel	Melting Practice	Chemical Composition					Acid Sol.		Maximum Increase in Transition Temp. After Straining and Aging	
		C	Mn	P	S	Si	Al	N	75° F	450° F
A	Liquid metal deoxidized with silicon and aluminum	0.25	0.56	0.017	0.028	0.13	0.013	0.011	86	112
B	Open hearth, capped	0.07	0.43	0.006	0.026	0.007	0.005	0.005	73	116
C	Bessemer, capped	0.08	0.47	0.075	0.032	0.012	0.006	0.016	147	209

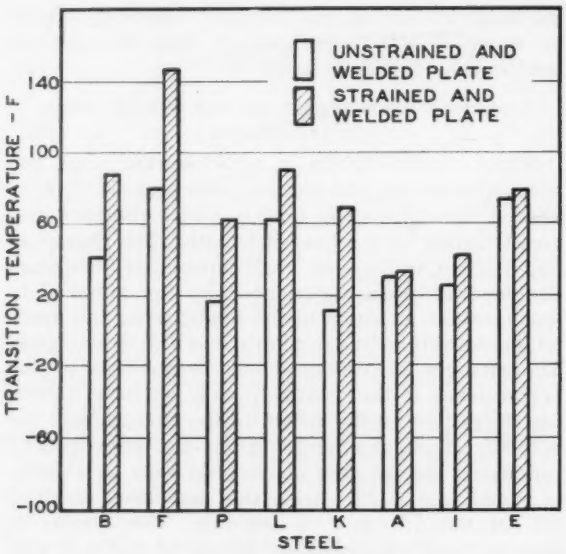

Figure 7. Effect of prior strain on the transition temperatures for a group of welded A-285 and A-201 steels in the Lehigh slow notch-bend test (Stout[26]).

considerably harder as a result of strain hardening. Furthermore, a system of residual stresses is set up on a microscopic scale in addition to any microscopic residual stresses that may have been produced. If a cold-worked metal is heated to a sufficiently high temperature, or held for a sufficiently long time at somewhat lower temperatures, recrystallization occurs, i.e., new strain-free grains are formed and begin to grow. For a given degree of cold work, the time required for complete recrystallization depends on temperature, being shorter the higher the temperature. The changes in properties brought about by recrystallization are in the direction of restoration of the original properties. The final properties of the recrystallized material may not be identical to those of the original material, however, because the grain size of the recrystallized material may differ from that of the original material.

Cold working has been defined earlier by implication as deformation under conditions such that strain hardening occurs. A definition can also be stated in terms of recrystallization, i.e., that cold work is plastic deformation carried out under conditions such that recrystallization does not occur as the material is being deformed. Hot work, on the other hand, is deformation carried out under conditions such that recrystallization occurs as the metal is being deformed.

Prior to the onset of actual recrystallization, a process known as recovery occurs, which may result in changes in some properties prior to the rapid softening accompanying the formation of new strain-free grains. Recovery is associated with the relaxation of microscopic residual stresses. A slight decrease in hardness may accompany recovery, but more noticeable changes are manifested as an increased proportional limit, decreased damping capacity, decrease in electrical resistivity, and other changes in physical properties.

The processes of recovery and recrystallization are of especial interest in their relationship to changes in properties that might occur upon heating cold-worked steel, for example, in the range of temperatures customarily used in stress relieving. The question naturally arises: Can the deleterious effects of cold work be removed by heating?

From a knowledge of the changes that occur during recrystallization, it would appear that the only certain method of removing the effects of cold work would be to bring about complete recrystallization of the material. Whether the notch toughness of the recrystallized material would be better than that of the original material would depend on the relative hardnesses and grain sizes. Under some conditions, for example in the recrystallization of very lightly cold-worked material, exaggerated grain growth may occur, so that the final grain size is a great deal larger than that of the original material, thereby partially offsetting the improvement brought about by recrystallization. Normalizing would be expected to eliminate the effects of cold work in that, not only would recrystallization and relief of cold-working effects occur on heating to the normalizing temperature, but also a completely new set of ferrite grains would be formed as the austenite existing at the normalizing temperature is transformed upon cooling.

Stout and co-workers investigated the effect of reheating cold-worked material for 1 hr. at 500, 800, 1,150 and 1,600° F on various properties, including

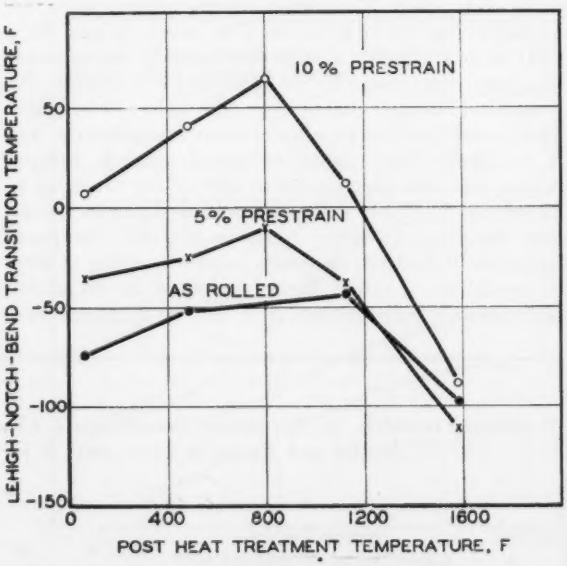

Figure 8. Effect of heating after prior tensile strain on the transition temperature of A-201 steel in the Lehigh slow notch-bend test (Stout[7]).

TABLE 5

Effect of Heating for One Hr. at 1050° F After 10% Strain on the Charpy Keyhole-Notch Transition Temperature for Three Alloy Steels

Steel	Initial Transition Temperature	Transition Temperature After 10% Strain	Transition Temperature After Straining 10% and Heating for 1 hr. at 1050° F
"T-1," heat A	—175	—155	—180
"T-1," heat B	—255	—222	—273
AISI 4815 (3.5% Ni, 0.25% Mo) (quenched and tempered)	—275	—247	—263
AISI 2315 (3.5% Ni) (normalized)	—250	—157	—220

notch toughness as measured in the Lehigh slow notch-bend test.[8] Typical results are shown in Fig. 8, which illustrates the behavior of 1¼-in. A-201 steel. The criterion of percent lateral contraction was used in evaluating transition temperatures. It can be seen that the maximum increase in transition temperature occurred at 800° F. The increased transition temperatures at 500 and 800° F can be attributed to strain aging. The transition temperatures observed after heating at 1,150° F are almost the same as for the cold-worked material. A similar observation was made by Smith and Garofalo[29] on the steels listed in Table 4 after heating 10 hr. at 900° F or 2 hr. at 1,200° F. This behavior might be attributed either to the possibility that strain aging is not occurring in this temperature range or to the possibility that the effects of strain aging are alleviated by changes associated with recovery. Examination of the steels indicated that recrystallization had not occurred. It is interesting to note that the yield stress of the Lehigh A-201 steel cold worked 5% drops from 58,800 psi to 49,400 psi as a result of heating at 1,150° F. The corresponding change in the material cold worked 10% was from 68,600 psi to 46,800 psi, strongly suggesting that recovery or incipient recrystallization has indeed occurred. More pronounced effects are evident in results of the notch toughness tests[20] conducted on ⅝-in. plates strained 20%, and heated for 1 hr. at 1,150° F. In the Lehigh slow notch-bend test, the transition temperature (on basis of percent lateral contraction) of the A-201 material was raised from −93 to —12° by 20% strain, but was lowered from −12 to —34° F by heating at 1,150° F after cold working. The response of the A-285 steel was even more pronounced, the transition temperature after treatment at 1,150° F being about the same as that of unstrained material. The transition temperature was raised from −46 to +43° F by 20% strain, and was lowered to —56° F by heating at 1,150° F.

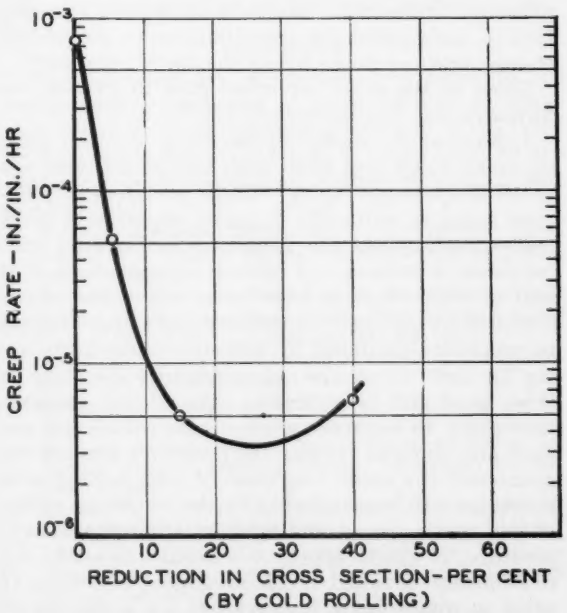

Figure 9. Effect of cold work on the creep rate of N-155 alloy under 50,000 psi at 1200° F (Frey and Freeman[32]).

Other limited data indicate that recovery possibly exerts a significant effect on notch toughness and in some instances may permit almost complete recovery of the notch toughness of the original material. In Table 5 are shown results of Charpy keyhole-notch impact tests on three steels: "T-1" steel,[27] quenched-and-tempered AISI 4815, and normalized-and-tempered 2315.[28] It can be seen that in every instance the transition temperature of the cold-worked material is very markedly lowered by heating at 1,050° F. On the basis of other tests, recrystallization is not believed to have occurred in these treatments. While it is not possible to advance an explanation at this time for the more pronounced response of these materials to heating, it may be significant that all of these steels have very fine ferritic grain sizes. It is known that for a given amount of cold work, fine-grained metals recrystallize more rapidly or will recrystallize at a lower temperature than coarser-grained material. It seems possible that changes associated with recovery also occur more rapidly in fine-grained material.

EFFECT OF COLD WORK ON ELEVATED TEMPERATURE PROPERTIES

The increase in strength at atmospheric temperature produced by cold working has already been discussed. At moderately elevated temperatures the increased strength will be retained and may be augmented by strain aging. As the temperature is further increased, however, the processes of recovery and recrystallization come into play and the contribution of cold work begins to be lost. Since the temperature at which recovery and recrystallization

proceed at an appreciable rate depends on the amount of cold work, it follows that for a particular service temperature there will be an optimum degree of cold work with respect to the increased strength that can be realized.[32] This principle is illustrated in Fig. 9.[33] for a high-temperature alloy, N 155.* Creep rates were determined at 1,200° F under a stress of 50,000 psi after various amounts of reduction at 80° F by cold rolling. It can be seen that a minimum in the creep-rate curve occurs at about 25% reduction.

EFFECT OF COLD WORK ON FATIGUE

The significance of fatigue in the service performance of pressure vessels is discussed by Dolan in the interpretive report "Fatigue as a Factor in Pressure Vessel Design."[34] In a discussion of the basic features of fatigue behavior, it is pointed out that for ferritic steels a "fatigue limit" exists, i.e., there is a stress below which the material will not fail in fatigue even though the stress cycle is repeated indefinitely. As the stress is raised above the "fatigue limit," the lifetime decreases, with lifetime of several million cycles generally being observed at stresses only slightly above the endurance limit. Lifetimes of primary interest in connection with pressure vessels are of the order of 100,000 cycles and less, since it is not likely that a greater number of pressure cycles would be experienced in the lifteime of most vessels. The stresses corresponding to these lifetimes would genrally be in the plastic region, at least in the early stages of cycling. Most of the work on fatigue of steels, on the other hand, has been concerned with the effect of different variables on the "fatigue limit" or the stresses corresponding to very long lifetimes. It is very well known, for example, that cold working raises the fatigue limit and that in steels susceptible to strain aging still further strengthening accrues from aging. Surface peening or cold rolling is commonly used to strengthen machine parts to be subjected to large numbers of cyclic stress application. A double benefit results from these treatments in that surface compressive stresses are set up in addition to the increased strength resulting from cold working.

In the range of lifetimes of concern in pressure vessel service, only recently has the fatigue problem been intensively studied, and work in this field is still in progress under the sponsorship of the Pressure Vessel Research Committee. Stout and coworkers[35, 36] have reported limited data as shown in Fig. 10 on the effect of cold work on the fatigue of A-201 and A-302 steels in the plastic region. Some increase in lifetime is observed as a result of 10% prestrain for the A-201 steel. For the A-302 steel, however, an increased lifetime was noted only at the lowest strain amplitude of slightly under 0.50%.

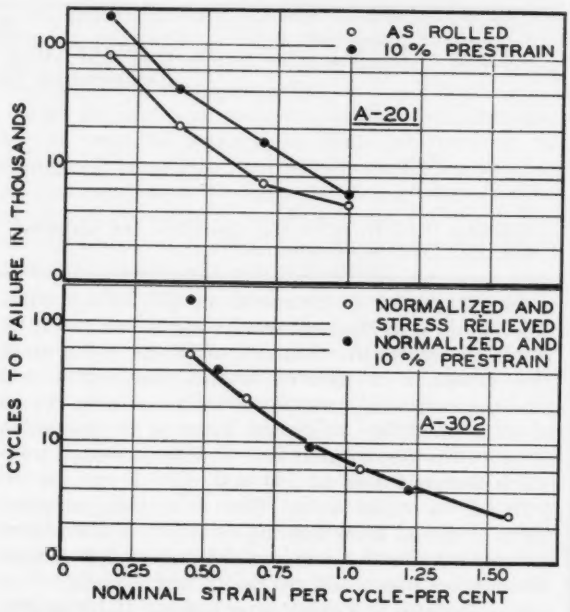

Figure 10. Effect of prior strain on the plastic fatigue resistance at A-201 and A-302 steels (Stout[35, 36]).

CONCLUSION

In conclusion it should again be emphasized that, from the practical point of view of material performance in a completed pressure vessel, the effects of cold work must be considered to include not only the direct and immediate changes, but also the subsequent changes for which the material is conditioned when cold worked. If logical steps are to be taken to minimize undesirable effects it is obviously important to understand the contributions to the overall change that are made by all the factors involved.

Some of the most important gaps in existing information can be summarized as follows:

1. Most of the studies of the effect of strain aging on notch toughness have been concerned with elevated-temperature aging. While elevated-temperature aging is naturally of great importance when cold-worked steels are subjected to elevated temperatures in subsequent fabrication operations, it is also of importance to know more about the effects produced by atmospheric-temperature aging. Changes in properties produced by elevated-temperature aging for short times are not necessarily the same as those produced by extended atmospheric temperature aging. In instances where stress relieving is not used and elevated service temperatures are not encountered, the notch toughness of cold-worked steel in service will be established by the combined effects of cold work, *per se*, and aging at atmospheric temperature. It would appear worthwhile to study the relationship between notch toughness and time of aging at atmospheric temperature for a number of widely used pressure-vessel steels. Not only would the results be of interest from a practical point of

* The nominal composition of N 155 is 20% Cr, 20% Ni, 20% Co, 3% Mo, 2% W, 1% Cb, 1% N, bal. Fe.

view, but also a better basis for setting up accelerated aging tests for simulating atmospheric-temperature aging would be provided.

2. The metallurgical changes occurring in cold worked steels in the range of customarily used stress-relieving temperatures and their effects on notch toughness are not well understood. While it appears that normalizing is the only certain way of restoring the original toughness of the material prior to cold working, heating at temperatures that would be encountered when stress-relieving in the temperature range of 1000° F and slightly above may be very beneficial under certain circumstances. Since in a few instances heating in this range appears to restore almost completely the original notch toughness, it is believed that the metallurgical factors influencing changes in this temperature region for pressure-vessel steels would be worthy of study.

3. Information on the effect of microstructure on the change in notch toughness produced by cold working is rather meager. With the current interest in the use of higher strength steels in pressure vessel construction, this question becomes one of practical interest. A systematic study of the effects on the response to cold work of variations in microstructure deliberately produced by control of heat treatment would be of value.

4. A better correlation of the effects of cold work produced in actual forming operations and effects of cold work produced by homogeneous straining in the laboratory would be very desirable. What are the amounts of cold work that are of primary interest? How does a non-uniform distribution of strain through the thickness of a plate affect the resistance of that plate to the propagation of a crack? Can the effect be adequately predicted from laboratory tests?

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The following list of references is provided for those readers interested in more detailed information regarding investigations referred to in the body of the report. References 1, 6, 8, 10, 21, and 29 are especially recommended for further reading in this general field.

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The Esso Shipping Company has placed orders for two tankers with a dead-weight of 37,800 tons and a speed of 18.3 knots, with Newport News Shipbuilding and Drydock Company. The Maritime Administration will finance, as a National Defense feature, the additions necessary for the extra speed of two knots.

Eagle Carrier, Inc, and Terminal Transport Corporation have each placed order with Ingalls Shipbuilding Corporation for a 26,000 tons dead-weight tanker.

HARRY H. RANSOM

SCIENTIFIC MANPOWER AND NATIONAL SECURITY

THE AUTHOR

is the Research Associate, Defense Studies Program, Graduate School of Public Administration, Harvard University. He received his Bachelor of Arts degree from Vanderbilt University in 1943 and his Master of Arts and Ph.D. from Princeton University in 1949 and 1954. He has taught Political Science at Princeton, Vassar College, and Michigan State University. He was Assistant Professor of Political Science at the latter institution when he came to Harvard in July, 1955. During 1953–54, Dr. Ransom was a "Congressional Fellow" of the American Political Science Association, working on Capitol Hill as a staff member for Senators and Congressmen.

In November, 1955, the then Chief of Naval Research made a speech to the Sixth Edison Foundation Institute, pointing out that only 125 new college-trained physics teachers were available that fall for the 28,000 high schools in the United States. A small statistic was this among many presented to the Institute, but one of far-reaching significance to the future security of the United States. Rear Admiral Frederick R. Furth was using this simple fact to spotlight the danger in another fact: that the Soviet Union is outgaining the United States in the training of scientists, engineers and technicians.

The growing shortage of scientists and engineers in the United States, and Russian progress in science and technology, are now well publicized. We have been surprised on more than one occasion by recent Soviet advances in weapons technology. Progress in nuclear weapons, long-range bombers, and Soviet seapower—Russia now has 430 submarines—has jolted our defense planners. But the long-range implications of a growing United States shortage of skilled manpower *vis-a-vis* Russia now must be recognized for what it is—a national crisis.

Are we as a nation willing to remain complacent to the threat that Russia, with her vast technical training programs, may outstrip us in technological development in the future? Are we to allow the crucial battle of brainpower—the cold war of the classrooms—to be lost by default? For in facing the two-pronged Soviet threat of economic and military competition, our national security rests upon the proper management of our vital manpower resources.

An example of this expanding Soviet technology was demonstrated on a blustery day in late March, 1956. Then a sleek, twin-jet Tupolev-104 passenger plane came down through the rain clouds to land at the London airport. Its cargo was "Ivan the Terrible" Serov, chief of Russia's security services, transported to England in a three-and-one-half hour, 1,564-mile flight from Moscow.

The TU-104 plane excited more attention than General Serov, in England to supervise security arrangements for the visit by Khrushchev and Bulganin. This *Aeroflot* jet airliner was "new evidence of the remarkable advances in aircraft design made by Russia during the last few years," according to a leading American aviation publication. It is powered by two of the largest turbo-jet engines operating in the world today.

While there is obviously no direct connection between the Soviet achievement of producing the TU-104 jet transport or 430 submarines and last fall's shortage in the United States of high school physics teachers, there is, however, a relationship here of

crucial importance to the nation's long-range strategic plans for security.

WINNING THE TECHNOLOGICAL RACE

We today are engaged in an arms race with the Soviets. It is becoming largely a race in military technology. The outcome may affect national survival. America's defense policy makers—both civilian and military—now are showing increasing awareness that this race may be won or lost in the field of research and development, and ultimately in the nation's classrooms.

Any plan to block Soviet expansion or to deter aggressive war by the Communists obviously must be based on a careful calculation of Soviet military potential. And plans to win any war we cannot deter must be the result of the most precise estimates possible of Russian strategic capabilities.

A nation's economic potential is one of the most relevant indicators of strategic capability. Realistic analyses of the foundations of national power have always taken into account scientific and technological skills—a basic ingredient of national economic strength and military potential. These skills now must be accorded an even greater importance in estimates of future strategic capability.

NEED FOR AN ACTION POLICY

An essential ingredient in an action policy for national survival and progress must include the building of an educational framework which will assure the required amount of skilled manpower. Elimination of the shortage of this essential element of national strength must be given a very high priority as the nation begins to implement its strategic plan for the "long haul."

The many immediate specific scientific problems involved in the development of complex weapons today tend to obscure the long-range consequences of our increasing dearth of skilled manpower. Current problems with strategic implications include: how to put successfully a man-made satellite in an encircling orbit around the earth; how to develop missiles with intercontinental range and accuracy; how to build atomic reactors to power ships and planes, or economically to heat, air-condition and light future cities; and how to solve the problem of the nation's dwindling natural resources.

Our success in these and other projects will constitute important variables in long-range strategic calculations. The strategic doctrines, composition, size and missions of our Navy, Army and Air Force of the future also will be profoundly affected by our achievements in these projects and by other unpredictable technological "breakthroughs." Whatever develops, it can be predicted with confidence that the need for well-trained scientists and engineers, both in and outside the military services, will increase constantly.

Our skilled manpower shortages, in one sense, are not a sign of failure but of outstanding success. For our natural resources, and form of government and economy, have created a situation in which demands made for superior skills in every field are but a sign of steady material progress. Even aside from the arms race with the Soviet Union, our future progress and prosperity, as well as our mi itary security, will depend upon a well-filled reservoir of trained manpower.

Yet a sense of urgency and crisis comes from published facts of the growing scientific and engineering capability of the Soviet Union. Encouragement may be found, however, in attention, if belated, now given this problem by U.S. policy-makers.

SOME SIGNIFICANT FACTS

Here are a few of the more significant cold facts, made public in recent months by government officials:

¶ Universities and technical institutions in Soviet Russia are graduating engineers in numbers some two and a half times greater than are similar institutions in the United States.

¶ The United States is now training only one-half its required number of engineers and scientists.

¶ A recent report of the Congressional Joint Atomic Committee (March, 1956) reveals that the combined total of engineers and scientists of the United States and 15 Western European nations is about 1,150,000. The Soviet Union total is 890,000 scientists and engineers, not including the satellites and Red China. The Soviet total exceeds that of the United States, and is more than three-fourths the number available in the free nations of Europe combined with the United States.

¶ Most experts seem to feel that Russian scientists and engineers in most fields cannot be considered inferior to our own.

¶ In the decade 1950-60, the Soviet Union is expected to produce 1,200,000 trained engineers and scientists compared to our 900,000.

¶ Even the combined advantage in this regard which the U. S. and countries of Western Europe has held is being seriously threatened by the Soviet Union.

¶ Half of our high schools teach no chemistry or physics. And much of the mathematics and science is being taught by teachers untrained in these fields.

¶ The number of qualified science teachers in the U. S. high schools has fallen off 53 per cent in the past five years, while high school students have increased by 16 per cent.

¶ In 1890, two generations ago, one in every five high school students in the United States studied physics. Today the figure is about one in every twenty-two.

¶ In the category of engineers alone, the Soviets have multiplied the numbers ten-fold since 1930, when records show they had 41,000 engineers.

Absolute accuracy of statistics on Soviet manpower cannot, of course, be assured. Not only do Soviet figures sometime have a questionable validity, there is also the difficulty of measuring quality. One might normally discount the kind of chest-thumping evident at the Twentieth Party Congress in Moscow (February 1956) over their claimed "superiority" in scientific personnel. Premier Nikoli Bulganin referred to technical experts as the Soviet Union's "gold reserve." Their current Five-Year Plan calls for four million new specialists by 1960. This would exceed the Soviet combined output of the two previous plans.

Yet obviously we do not have to look to Communist propaganda to discover cause for concern. The words of our own government officials—both civilian and military—and the unclassified facts, such as those above, are alarming enough.

THE CATFISH AND THE HERRING

The British historian Arnold J. Toynbee tells the story, when discussing the Free World-Soviet struggle, of the catfish and the herring. There was a fisherman who continually returned to port with a catch of herring far fresher than that of his colleagues. His fish brought a higher price. Eventually the other fishermen discovered his secret. The cagy fisherman always deposited a live and hungry catfish into the tank containing his home-bound load of herring. The herring were thus kept active on the voyage to market by attempting to avoid the jaws of the catfish. A few herring were lost enroute, but most of them arrived in port alive, fresh and highly marketable.

The Soviet "catfish" has brought critical self-examination to the West in many fields. These include our sea power, guided missiles and air power. None the least of these in long-range importance, however, is the need for more trained scientific and engineering personnel than are now being produced or projected for the future. This need is more often discussed today in terms of development of weapons in the armament race with the Soviet Union. And weapons, of course, constitute an urgent consideration in view of Soviet achievements in this field. But this is only one side of the coin.

EXPORTABLE TECHNICIANS AND THE COLD WAR

Secretary of State John Foster Dulles and Atomic Energy Commission Chairman Lewis L. Strauss have been explaining that the long-range security of the United States, and perhaps even the outcome of the cold war, may be acutely affected by a continuing shortage of scientists, engineers and other technicians. A neglected prospect, expressed by Secretary Dulles and others, is that the Soviet Union's ability may surpass ours to raise and disperse a force of technical assistants all over Asia and Africa. Looking ahead ten years, Secretary Dulles has voiced concern, not that the Soviets will have a true, exportable surplus of capital or goods, but an exportable surplus of technicians. And these will not be just qualified scientists and engineers, but the same individuals will be well-trained in the art of political subversion.

The United States, already running short of scientists and engineers, may not be able to compete effectively with Soviet offers of this kind of technical aid to the "uncommitted areas." The solution to this grave national security problem demands attention in the highest councils of government.

Those concerned with the implications of scientific and engineering manpower to national strategy will do well to consult three important and easily available recent publications relating to this problem. These are, the report of Congressman Melvin Price's Subcommittee on Research and Development, Congressional Joint Committee on Atomic Energy, *Engineering and Scientific Manpower in the United States, Western Europe and Soviet Russia* (March 1956); the more recent *Hearings* of this same Committee, *Shortage of Scientific and Engineering Manpower,* (July, 1956); and Dr. Nicholas DeWitt's *Soviet Professional Manpower: Its Education, Training and Supply* (National Science Foundation, Washington, 1955).

TOWARDS A SOLUTION

Although the situation can be called critical, an action program must be based on the most careful examination and diagnosis of the causes of the present and impending shortages of skilled manpower. No "crash program" can magically produce the numbers and quality of trained personnel needed for the nation's future prosperity and military security. These can be produced only as the result of carefully-prepared plans for readjustment of our total educational system. Certainly enough facts will be at hand when the National Committee for the Development of Scientists and Engineers, recently appointed by President Eisenhower, makes its report.

There is a mass of information already available which offers clues toward a solution to the problem. It is well known that millions of American youth have been denied adequate educational opportunities. Countless words have been written, and hundreds of pages of testimony taken, about the urgent need for more school teachers, more school construction, and improved curricula. Because of complex political, social and economic factors, however, these needs are being met only with agonizing slowness. The matrix of federalism, intergovernmental competition for the tax dollar, unhealthy condition of many state and local financial structures, and disagreement on solutions both among professional educators and among politicians, seem at first glance to be insurmountable obstacles. Yet these must be faced before adequate solutions can be found.

Information is already available indicating one important area where weakness exists. It is known that in the United States only half of the high school graduates who are potential science and engineering students enter college. And less than half of these who embark on science and engineering studies actually complete their work for a college degree in these fields. There is obviously a high degree of loss, then, in high school, between high school and college, and in college. This amounts, in fact, to an 80 per cent wastage of potential engineering and science talent, for of every ten high school students with theoretical capacity for potential careers in science and engineering, only two actually earn the college degree.[1]

A major factor in this attrition is an economic one. College education is becoming increasingly expen-

[1] Congressional Joint Committee on Atomic Energy, *Engineering and Scientific Manpower,* pp. 33-34.

sive. Although the availability of scholarship money has increased, the "buying power" of scholarships has decreased. The problem can be solved only with increased financial aid from private corporations, the educational foundations, individual donors, and the Federal and State governments. Surely, the Federal Government's role will have to be a major one in the provision of scholarships, teacher training and physical plant. Attention must not be directed, however, at the college-level alone, for the problem has roots in the secondary, and even elementary, school systems.

There is a long and disturbing history of decreasing interest at the high school level in subjects basic to college study of engineering and science, particularly mathematics, but also chemistry and physics. What seems to be a decreasing interest, however, may only be the result of two factors: a shortage of competent teachers and an overemphasis, in planning the curriculum, on "generalized" education.

The number of college-trained scientists and engineers also is steadily declining. Graduates in engineering and science who received degrees with the class of 1950 comprised nearly 25 per cent of the entire class. In 1954, these represented about 18 per cent. According to predictions, those of the class of 1960 will comprise a bare 15 per cent of the total number of college graduates.

REPAIRING THE EDUCATIONAL FABRIC

The total fabric of our educational system needs repair. It is somewhat surprising that in an age of technology this nation, whose technology surpasses all, should find itself facing serious shortages in such a vital resource as skilled manpower. This argument, parenthetically, should not be taken as one for de-emphasizing liberal arts education, particularly the social sciences. To the contrary, it should be noted that the increasing complexity of our technological society demands extra attention by social scientists.

Our chief competitor, Soviet Russia, long ago faced this problem with a dogged determination not to be caught short. Russian technological achievements—such as that TU-104 which landed in London last March—result from an intensive kindergarten to graduate school program over the past several decades to assure an adequate supply of scientists and technicians. If they surpass us in this human resource, they gain a crucial long-range advantage in a primary element of military and industrial strength.

THREAT COMPARABLE TO SOVIET MILITARY POWER

We may take some comfort in faith that our spirit of academic freedom, which does not exist in Russia, is a built-in guarantee of superior ability. But this is no excuse for complacency. For Russia's classrooms, laboratories, and ambitious and effective plans for mass education pose a threat to our future security comparable to her long-range submarines, bombers and guided missiles and massive military manpower. The need for a well-conceived strategic plan for maintaining technological supremacy for the United States is urgent. In the words of President James R. Killian, Jr. of MIT, "our national security can be jeopardized, and even lost, by the mismanagement of our resources—both proved and potential—of creative intelligence."

One of the new guided-missile frigates authorized for construction in fiscal year 1956 will be named the USS KING, in honor of the late Fleet Admiral Ernest J. King (a past president of ASNE). The keel of the KING will be laid sometime in 1957 at the Puget Sound Naval Shipyard. She will have an extreme beam of 50 feet, 512 feet in length and displace 3,900 tons. The KING will be equipped with TERRIER guided-missiles aft and 5-inch gun batteries forward.

"JOURNAL OF THE INSTITUTE OF METALS"

METALLURGICAL RESEARCH AND DEVELOPMENT FOR NUCLEAR POWER

ACKNOWLEDGEMENT

This article, published in the March, 1956, issue of "The Journal of the Institute of Metals," was written by Dr. H. K. Hardy, Research Manager, U. K. Atomic Energy Authority.

INTRODUCTION

THERE IS EVERY reason to suppose that the use of electrical power in Great Britain will continue to grow, and in twenty years' time the consumption may easily reach more than three times the present level. It would be very difficult to meet the anticipated demand from the expected coal supplies, although an extension of the use of oil for coal might provide some relief. It is, therefore essential to take advantage of the only other major source of power available to this country—power from nuclear energy. A short analysis has been presented in a Government White Paper [1] which envisages the construction in Great Britain during the next ten years of nuclear power stations with a capacity of about 1500-2000 MW. On the assumption that these are to be used as base-load stations, nuclear power would be providing electricity equivalent to that produced annually by 5-6 million tons of coal or about a quarter of the requirement for new generating capacity. The White Paper anticipated that the rate of new utilization of nuclear energy relative to conventional fuels would increase from 1965 onwards, when the feasibility of using it had been demonstrated on a large scale.

The change-over from conventionally fueled power stations to those incorporating nuclear reactors involves the solution of the many problems inherent in the development of a new technology. These solutions must be found by predetermined dates, if the time-table laid down in the White Paper for the change-over is to be met. The present paper concentrates on one important aspect of the nuclear-power program—the interdependence of metallurgical research and development of fuel elements and the design and construction of nuclear reactors.

For a given power rating, a fuel element must stand up to certain conditions of irradiation which depend upon the principles of nuclear fission and reactor physics. Economic production of electricity is controlled by a number of engineering considerations, among which the operating conditions of the fuel elements are of prime importance. The temperature at which a fuel element can work is governed largely by its metallurgical properties, and these in turn are closely connected with its environment. The decision to build a power reactor involves the preparation of a time-table for the program of necessary research and development work. The extent to which problems can be investigated is related to the time-table for the construction of the reactor itself, since results must be available when they are required.

Progress in the production of electricity by the utilization of nuclear energy is limited at present more by the rate at which improved materials, especially better fuel elements, can be developed than by the rate of extension of reactor physics.

POWER FROM CONTROLLED NUCLEAR FISSION [2, 3]

The energy changes involved in a modification of the central nucleus of an atom are about a million times greater than those involved in chemical reactions, such as the burning of coal. It is the purpose of a nuclear reactor to achieve the release of energy on this scale in a controlled and usable manner. Nuclear fission is the name given to the reaction in which a free neutron, the uncharged constituent of the nucleus, strikes the nucleus of a fissile element and causes it to split into two fragments of slightly dissimilar mass.

Natural uranium consists essentially of a mixture of two main isotopes: uranium^{238} 99.3% and ura-

nium^{235} 0.7%. Of these two naturally occurring isotopes, only uranium^{235} undergoes fission on the capture of a low-energy neutron; these are termed thermal or slow neutrons.* The following is a typical fission reaction:

$_{92}U^{235} + _0n^1 \rightarrow _{92}U^{236}$ (excited) $\rightarrow _{38}Sr^{94} + _{54}Xe^{140} + 2_0n^1$

The fission fragments, which may themselves be radioactive, range in mass from about 80 to 160. Insertion of the exact figures for the atomic masses in the above reaction shows that fission has been accompanied by the disappearance of about 0.22 atomic mass units, which is converted into energy to the extent of about 200 MeV./fission.

The number of fissions per second required to produce power at the rate of one watt † may therefore be calculated to be 3.1×10^{10}. The complete fission of one gram of uranium^{235} per day provides an energy release at the rate of 10^6 W. or 1 MW.† Consequently, a reactor operating at a specific power rating of 1 MW./tonne of uranium (i.e. 1 MW./10^6g.) loses 1 g. of uranium^{235} per day, while each gram of fuel produces heat at the rate of 1 W. The effective neutron flux (i.e. the neutrons actually producing fission) necessary to produce heat at this rate is about 3.2×10^{12} neutrons/sec./cm.^{2}.‡ If one tonne of fuel were to remain in the reactor for 1000 days "burning" at the rate of 1 MW./tonne, the irradiation achieved would be measured as 1000 MW. days/tonne (MWD/T), which is equivalent to a "burnup" of 0.1% of the atoms originally present. During an irradiation of 1 MWD/T the fuel is subjected to a total of integrated effective flux of about 2.7×10^{20} neutrons/cm.^{2}.

On the average, each fission process releases 2.5 neutrons. A self-sustaining chain reaction, that is the continuous fission of atoms due to the continuous generation of neutrons, will be possible only if at least one neutron per fission collides successfully with another fissile nucleus. However, not all the neutrons thrown out by fission are available to propagate the chain reaction. Some of them are captured by the nuclei of neighboring non-fissile atoms, such as uranium.^{238} (This then becomes uranium^{239}, which is radioactive and decays rapidly to plutonium^{239}). Some of the neutrons will be used non-productively by absorption in the fuel and previously created fission products or by other materials in the reactor. Others will be lost from the reactor by leakage. The neutron economy of the reactor is clearly of prime importance and represents a problem to be solved in the design. Reactor control depends on maintaining the neutron balance, i.e. a steady-state flux distribution, and is exercised by the automatic insertion or withdrawal of a material which absorbs neutrons.

The leakage of neutrons from a reactor leads to a minimum critical size below which a self-sustaining chain reaction cannot be established because an insufficient number of neutrons are retained. It follows, both in principle and in practice, that a very small-scale working model of a reactor cannot be built to demonstrate the production of power. The small piles constructed for reactor research, such as GLEEP (Graphite Low Energy Experimental Pile) and ZEPHYR (Zero Energy Plutonium Fast Reactor) at Harwell, are essentially low-energy reactors with very low specific power ratings. GLEEP has only a superficial cooling system and develops a maximum flux of about 3.7×10^{10} neutrons/sec./cm.^{2} at 100 kW.[4] The high-density neutron fluxes necessary for large-scale power productions are possible only in a large reactor of natural uranium or in a correspondingly smaller reactor containing fuel enriched in a fissile element. Provided that the design can create a large volume at a uniform flux density, the upper limit of size is fixed by engineering and material considerations.

It remains to extract the heat from the fuel in the reactor by a coolant. The heat flux across the surface of a bar of uranium 2.5 cm. in dia.|| "burning" at the rating of 1 MW./tonne would be about 12 W./cm.^{2}. This value is closely comparable to that experienced from an ordinary domestic electric fire, since a 1-kW. element, 25 cm. long and 1.25 cm. in dia., gives off about 10 W./cm.^{2}

TYPES OF NUCLEAR-POWER REACTORS

The neutrons generated on fission possess an energy of the order of 1 MeV. and are termed "fast" neutrons. Uranium^{235} is more readily fissioned by slow or "thermal" neutrons, but uranium^{238} is more readily transformed into plutonium^{239} by fast neutrons. Plutonium^{239}, which is a by-product of the liberation of power by a thermal reactor, is fissile. It is now believed probable that plutonium, separated from the spent thermal-reactor fuel or made in special reactors, could be used in a fast reactor to create from uranium^{238} more plutonium than was consumed. The new plutonium could be fed back into the thermal reactors to make good the depletion in uranium^{235}.

The development of an economic fuel cycle [5] hinges on developments in reactor design. Nuclear reactors can be classified into two main types, thermal and fast, according to the energies chiefly responsible for fission.

The essential feature distinguishing a thermal reactor is that the fuel is dispersed in a "moderator," which moderates, or reduces, the average speed of the neutrons produced by fission, to a low value known as the thermal-equilibrium level, so that the chain reaction may be perpetuated by fission of uranium^{235}. The parasitic absorption of neutrons in the moderator must be as low as possible, and four

* Slow neutrons have an energy less than 0.1 eV. At room temperature their most probable velocity is 2200 m./sec. corresponding to 0.025 eV.

† One watt = 0.24 cal./sec.; the physical significance of an energy release at the rate of one megawatt may be clarified by the statement that this would provide enough boiling water for about 10–15 cups of tea/sec., depending on the efficiency and operation of the boiler.

‡ Calculated from the relationship that the rate of fission is equal to the number of atoms in the fuel × the "cross-section" of the fuel atoms for the capture of a neutron which causes fission × the number of neutrons, all in the appropriate units:
$(3.1 \times 10^{10}$ fissions/sec./g. $\times$ 19 g./cm.$^3) =$
$(0.47 \times 10^{22}$ atoms/cm.$^3 \times 3.92 \times 10^{-24}$ cm.$^2 \times$ neutrons/sec./cm.$^2)$
In practice the BEPO pile at Harwell [4] operates at a maximum flux of 2×10^{12} neutrons/sec./cm.^{2}.

|| Published figures show that the fuel rods for a graphite-moderated thermal reactor are frequently about 2.5 cm. in dia., e.g. in BEPO at Harwell the fuel is 2.29 cm. in dia.[4]

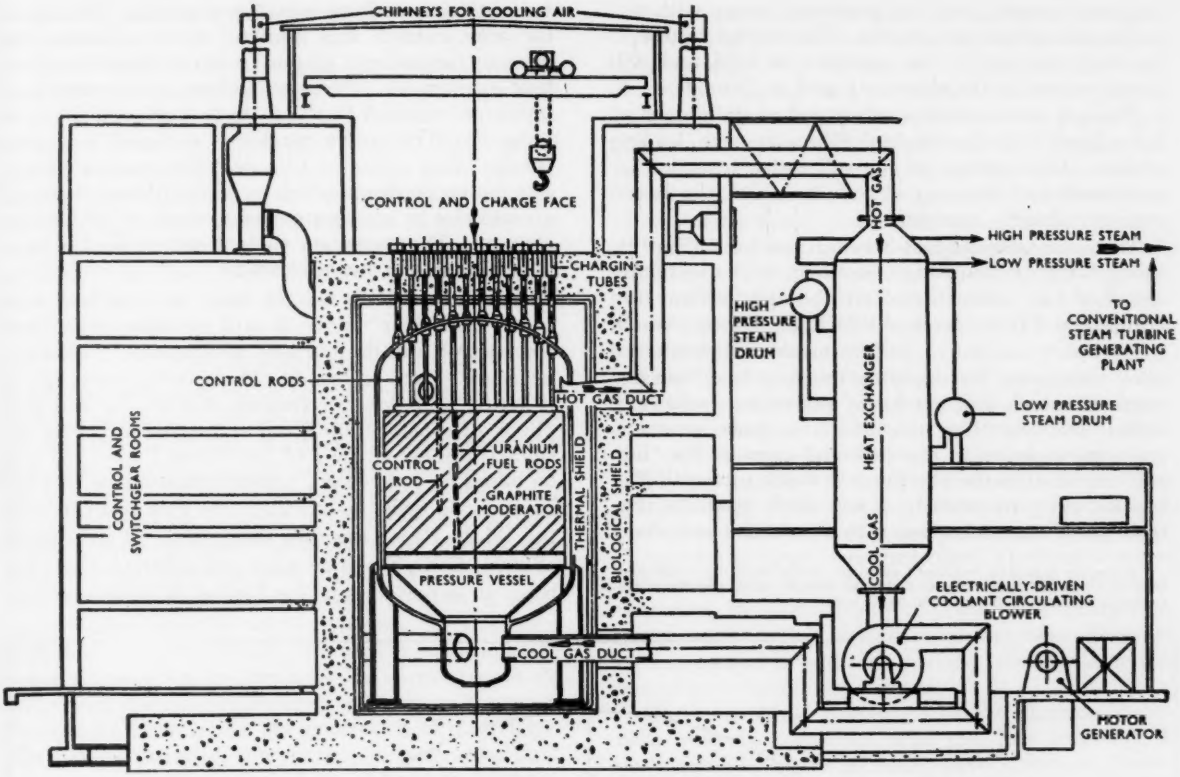

Figure 1. Diagrammatic Cross-Section Through the Calder Hall Type of Gas-Cooled Thermal Reactor.

possible elements for use in moderators may be considered: carbon (usually as graphite), light hydrogen (usualy as light water), heavy hydrogen (usually as heavy water) and beryllium (perhaps as beryllia). The coolant may be a gas, such as carbon dioxide or helium, or a liquid such as light or heavy water or molten sodium. The uranium has to be protected from oxidation or corrosion and, as always, neutron economy has to be considered. Possible canning materials for thermal reactors are beryllium, magnesium, aluminum, and hafnium-free zirconium.

In a fast reactor, the neutrons are not slowed down, but are allowed to cause fission while they still retain most of the energy with which they are generated. The absence of a moderator leads to an active core of very small volume in which heat is liberated. The high heat ratings probably demand the use of a liquid coolant. However, a wider choice of canning materials is available than for thermal reactors, because the absorption cross-section for fast neutrons is generally lower than for thermal neutrons. Possible materials include stainless steel, vanadium, niobium, tungsten, tantalum, and molybdenum.

An essential difference between thermal and fast reactors is that the former can use natural or only slightly enriched uranium, whereas a fast reactor requires that the fuel contain an appreciably higher concentration of a fissile element than occurs in natural uranium. There is, therefore, an economic advantage in building thermal reactors at the beginning of a program to obtain power from nuclear energy. Both thermal and fast reactors capable of producing power are under construction for the United Kingdom Atomic Energy Authority.[6]

The Calder Hall type of thermal reactor[7] (Fig. 1) is contained in a 2-in.-thick welded-steel pressure shell about 40 ft. in dia. and 60 ft. high, which will operate at a service temperature probably in excess of 350° C. The pressure shell is surrounded by a 6-in.-thick mild-steel thermal shield to protect the concrete biological shield, which is about 7 ft. thick. The core of the reactor is built up from many thousands of separately and accurately machined graphite blocks. The weight of the graphite, more than 1000 tons, is carried by a 4-in. steel base-plate supported by brackets through the pressure-vessel wall on to ten inverted A-frames resting on the bottom thermal shield, and 11-ft.-deep concrete foundations. The fuel elements are charged and discharged through stations in the top pressure dome into vertical channels in the graphite. Twenty-five tons of carbon dioxide are needed to charge the reactor and coolant circuits at a pressure of 100 lb./in.^{2}. The carbon dioxide is forced vertically upwards over the fuel elements and then passes to four heat-exchangers 70 ft. high and 18 ft. in dia. Steam from the

heat-exchangers goes to a generator house with two turbo-generators per reactor. The reactor is due to be commissioned in the summer of 1956 and will supply power to the electricity grid in October.

There is one control or safety rod of stainless-steel tube lined with boron-steel fillers at each loading station. The reactor is controlled by insertion or withdrawal of the control rods in which the boron strongly absorbs neutrons.

The experimental fast-breeder reactor [6] (Fig. 2), being built at Dounreay, Scotland, will use highly enriched fuel, either uranium ^{235} or plutonium, in a core about 2 ft. in dia. and 2 ft. high, through which the primary coolant of sodium or sodium-potassium alloy circulates. Surrounding the core is a "breeder blanket" which will consist of cartridges containing either uranium ^{238} or thorium. The spare neutrons from the reaction in the core will convert the "fertile" material in the blanket into fissile material. The blanket is surrounded by a 4-ft.-thick graphite neutron shield containing boron to protect the secondary coolant from activity-inducing neutrons. The annular area outside this neutron shield contains the primary/secondary (liquid sodium/liquid sodium) heat-exchangers, which are in turn surrounded by a biological shield 5 ft. thick, 45 ft. high, and 90 ft. in outer dia. The entire reactor is enclosed in a steel sphere 135 ft. in dia. × 1 in. thick designed to contain any fission products which might be liberated should a rapid rise in temperature cause melting of the fuel elements. The secondary coolant carries the heat to a boiler house for steam raising.

The Calder Hall reactor may be classified as a power-converter* since it will produce heat (and electricity) and the burn-up of uranium ^{235} converts uranium ^{238} into plutonium. The specific power rating is stated to be low for reasons of economy and simplicity of construction. Civil units are now being designed to meet Stage I of the White Paper and will be based on gas-cooled, graphite-moderated thermal reactors. In order to calculate the cost of electricity, the White Paper assumes that a level of irradiation of 3000 MWD/T will be achieved, although there has been no experience in the United Kingdom of irra-

* A reactor is said to "convert" when the fissile offspring is different from the original fissile element and to "breed" when the fissile offspring is the same as the original fissile element.

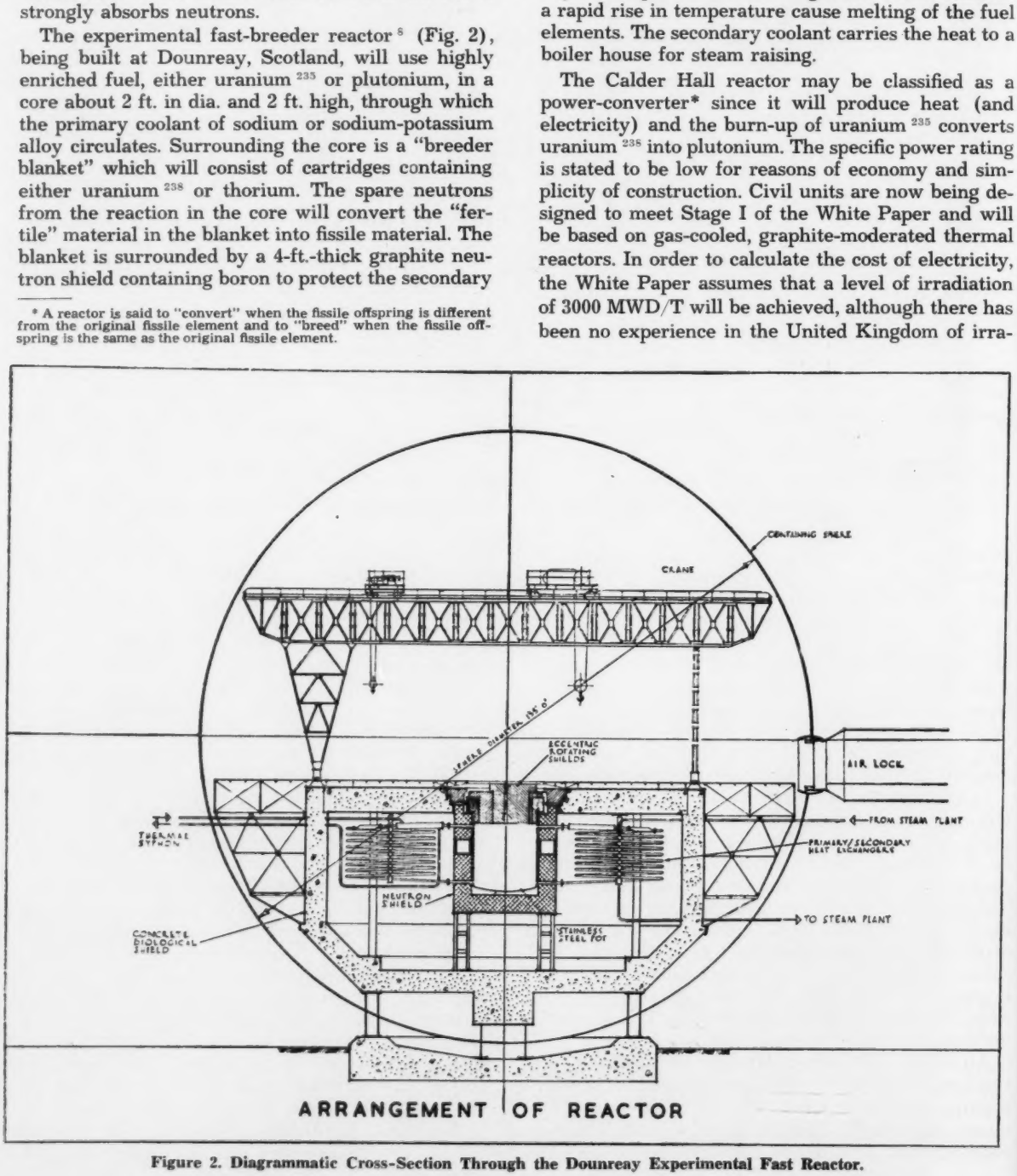

Figure 2. Diagrammatic Cross-Section Through the Dounreay Experimental Fast Reactor.

diation to such a high level at a reasonably high temperature.

The Dounreay experimental fast reactor may be classified as a power-breeder, since it produces heat (and electricity) and the burn-up of plutonium "breeds" plutonium from uranium ^{238}. The rate of heat liberation has been given as 60 MW. On the assumptions that all the heat is generated in the core (2 ft. × 2 ft. dia.) and that half the volume of the core is occupied by the fuel, the specific power rating works out at about 40 MW./tonne, which would require a neutron flux of the order of 10^{14} neutrons/sec./cm.^{2}.

FUEL ELEMENTS

The reactor must be so designed that the correct neutron conditions are obtained, and means of controlling the reactor, of charging and discharging the fuel, and of extracting the heat from the fuel at the desired temperature must be included. The heat from the fissile material has to be conveyed to a heat-exchanger which raises the temperature of the steam used to drive the turbo-generators. The properties of the reactor coolant are important because it must neither unnecessarily waste neutrons nor possess a high induced radioactivity. The danger of radioactive contamination has so far made it impossible to do away with the heat-exchangers, and to use the reactor coolant directly for the generation of electricity. The cost of pumping the coolant is very important, because it absorbs much of the difference between the gross and net electrical outputs of the reactor.

The fuel element is essentially the fissile material contained in a can. The can may serve to locate the fuel in the reactor and possibly to keep the fuel out of contact with the coolant, since the fissile materials, such as uranium or thorium, are usually very reactive chemically. The fuel element has to operate within the coolant under irradiation and at elevated temperatures.

Current fuel elements may be classified into three types: (i) those in which bars or slabs of the fuel provide the strength, in a weak can, (ii) those with a strong canning material which supports the bars or slabs of the fuel and (iii) those in which the fuel is present as small discrete particles distributed throughout a non-fissile matrix.[9, 10]

In every case good heat-transfer characteristics are of prime importance, and the fuel may be bonded to the can in order to reduce the temperature drop at the fuel/can interface. Whether the fuel be bonded or unbonded, the dimensions must be closely controlled so that the fuel is a good fit in the can and that the weight of uranium in each element is accurate. The external dimensions of the can also must be held within close limits to prevent misalignment in the reactor and interference with the flow of coolant. The heat-transfer characteristics of the element must not only be as good as possible but must also be reproducible under production conditions.

Provided that the temperature is not too high, fuel elements operating in gaseous coolants generally have fins, as the cans can be made from aluminum or magnesium alloys possessing a high thermal conductivity. Finning does not increase the heat transfer at higher operating temperatures which necessitate the use of higher-melting-point metals, as these possess a lower thermal conductivity. Fuel elements for liquid-cooled reactors will generally be free from fins, because these would interfere with the passage of the coolant and increase the pumping power needed. The heat transfer can be improved by increasing the surface area of the fuel element, provided that this does not run counter to the neutron requirements of the reactor.

The canning material must be compatible with both the coolant and the fuel. This means that the can must neither oxidize nor otherwise react with the coolant, nor be adversely affected by any impurities normally present in the coolant. Depending on the design of the reactor, the can may be required to contain all the fission products, which would be dangerous or toxic if uncontrolled. The fuel and the can must not react at the operating temperature, therefore, or alternatively any potential interaction which might lead to leaks through the can walls must be suppressed by suitable surface treatments or the use of non-reactive interlayers.

The mechanical properties of the canning materials must be consistent with the duty imposed. A weak canning material must have sufficient creep-ductility to conform to any changes in shape of the fuel in order that the fuel and can may remain in close contact. A strong canning alloy must have sufficient creep strength under irradiation to locate and support the fuel.

Canning materials necessarily waste neutrons. In general, the neutron absorption is the most important consideration in fuel elements for thermal reactors, whereas high melting point, and possibly also the strength at high temperatures, are more significant in fuel elements for fast reactors which operate at higher temperatures.

The fuel element must be dimensionally stable at elevated and fluctuating temperatures, and under irradiation at the selected power rating. Under neutron bombardment all materials are susceptible to irradiation damage, for example, the creation of lattice vacancies and interstitial atoms. In principle, it is to be expected that the damage will be less in the non-fissile materials, such as the can and moderator, than in the fuel, which is subjected to very intense and very localized heating at each fission process. Accumulated experience bears out this generalization, at least when the non-fissile materials are compared with uranium fuels. The results suggest that the irradiation damage in canning materials and graphite is not very serious.

Uranium exists in three allotropic modifications; α, which is orthorhombic and stable up to about 660° C.; β, which is tetragonal and stable in the range 660°–760° C.; and γ, which is body-centered cubic,

stable from 760° to the melting point at 1133° C. The thermal expansion coefficients of α-uranium depend on the crystallographic direction; over the range 25°–650° C., the values parallel to the *a*, *b*, and *c* axes are respectively 36.7, −9.3, and 34.2 × 10^{-6}/°C.[11] Heating of polycrystalline uranium therefore causes stresses between neighboring grains, and dimensional changes can occur in specimens when thermally cycled in the α phase. Random orientation increases the amount of internal microscopic deformation, but minimizes the dimensional change, which will normally be small; preferred orientation minimizes the internal microscopic deformation, but accentuates unidirectional change of shape, which may reach several hundred per cent.[11, 12]

There is an increase of volume in passing from the α to the β phase, and the transformation strains will be a function of the crystallographic orientations between the phases and of their relative strengths. Thermal cycling through the α–β transition temperature causes deformation of uranium specimens. Cycling a cylinder of cast uranium in a radial heat flux generally brings about a diametrical expansion and a longitudinal contraction. The surface of the specimen is roughened, while prolonged cycling causes cracks and internal voids; the deformation suffered may be decreased by alloying. Thermal-cycling tests are used to sort materials for irradiation tests. Although there is not complete correspondence, it is believed that materials unstable under thermal cycling will also be unstable under irradiation, while materials stable to thermal cycling are more likely to be stable under irradiation.

Of the 200 MeV. produced by each fission process, about 170 MeV. appears as kinetic energy of the fission fragments and is dissipated by strong interaction with the surrounding atoms of the fuel. The rapid intense local heating and cooling produces internal microstresses and deformation of the crystal. This type of irradiation damage becomes less severe at higher temperatures, but may be replaced by other forms of damage such as the creation of voids, perhaps by the accumulation of the fission-product gases, xenon and krypton. Two new atoms are produced at each fission process; allowance for the atomic volumes shows that the atoms will occupy a volume greater than twice the volume of the fissioned uranium.

Absolute stability of the fuel under irradiation may eventually be less important than the ability to predict in detail the changes that will occur, a situation which has not yet been reached. The fullest possible stability of the fuel is the present aim, so that the limited information on the behavior under irradiation may be extrapolated more confidently to the burn-ups required from fuel elements for nuclear-power reactors. Stability of the dimensions, physical and mechanical properties, and a knowledge of the changes in nuclear properties under irradiation are all very important. For example, dimensional changes might adversely affect the heat transfer or disrupt the can, while an unexpectedly rapid fall in the reactivity of the fuel because of build-up of fission-product "poisons" might limit the ultimate useful life of the fuel elements in a given reactor. The performance of the reactor and the economic cost of electricity from nuclear energy are intimately dependent on the behavior of the fuel elements under irradiation.

FUEL-ELEMENT DEVELOPMENT TO A TIME-TABLE

Construction of a power reactor is a large-scale engineering undertaking. Every aspect of the work needs to be closely planned so that each shall make its proper contribution to the project at the correct time. Attention will be directed here to the manner in which the metallurgical research and development program must be controlled in order to render possible the large-scale production, to a rigid specification, of several thousands of fuel elements per reactor.

Fig. 3 illustrates the consequences that follow a decision to undertake the heavy investment, both of money and man-power, involved in building a power reactor. The example is completely hypothetical, and the effort has been allocated on the basis that electrical power will be expected five years after a firm decision has been made to design. An extensive theoretical, experimental, and economic survey must precede the decision, and this must support the assumption that any necessary technological developments can be attained reasonably in the time available. It appears valid to assign about one year to charging the fuel elements, carrying out the commissioning and operating tests, and working up to full power production. This means that the reactor must have been built and that the fuel elements must be ready at the end of the fourth year, which in turn implies that, apart from trivialities, the main design has been completed a year earlier. It is desirable to spread the construction of the reactor and accompanying equipment, such as heat-exchangers and turbo-alternators, over about three years. Consequently the general arrangements have to be fixed in the first year and should follow logically from the feasibility studies.

The operating conditions for the fuel elements can be outlined about the same time, and the preliminary specification should be available shortly afterwards. By this time the coolant, the neutron flux, the heat flux, the temperature distribution ,and method of fuel-element support should be defined, together with the shape, dimensions, and weight of the fuel and cans.

Assuming that the extraction metallurgy program is being laid down separately, the operations in the manufacture of the fuel elements may include melting and casting, alloying, working, heat-treatment, machining, straightening, inspection, canning, sealing, cleaning, and testing. If the plant for the production of the fuel and the canning operations has to be

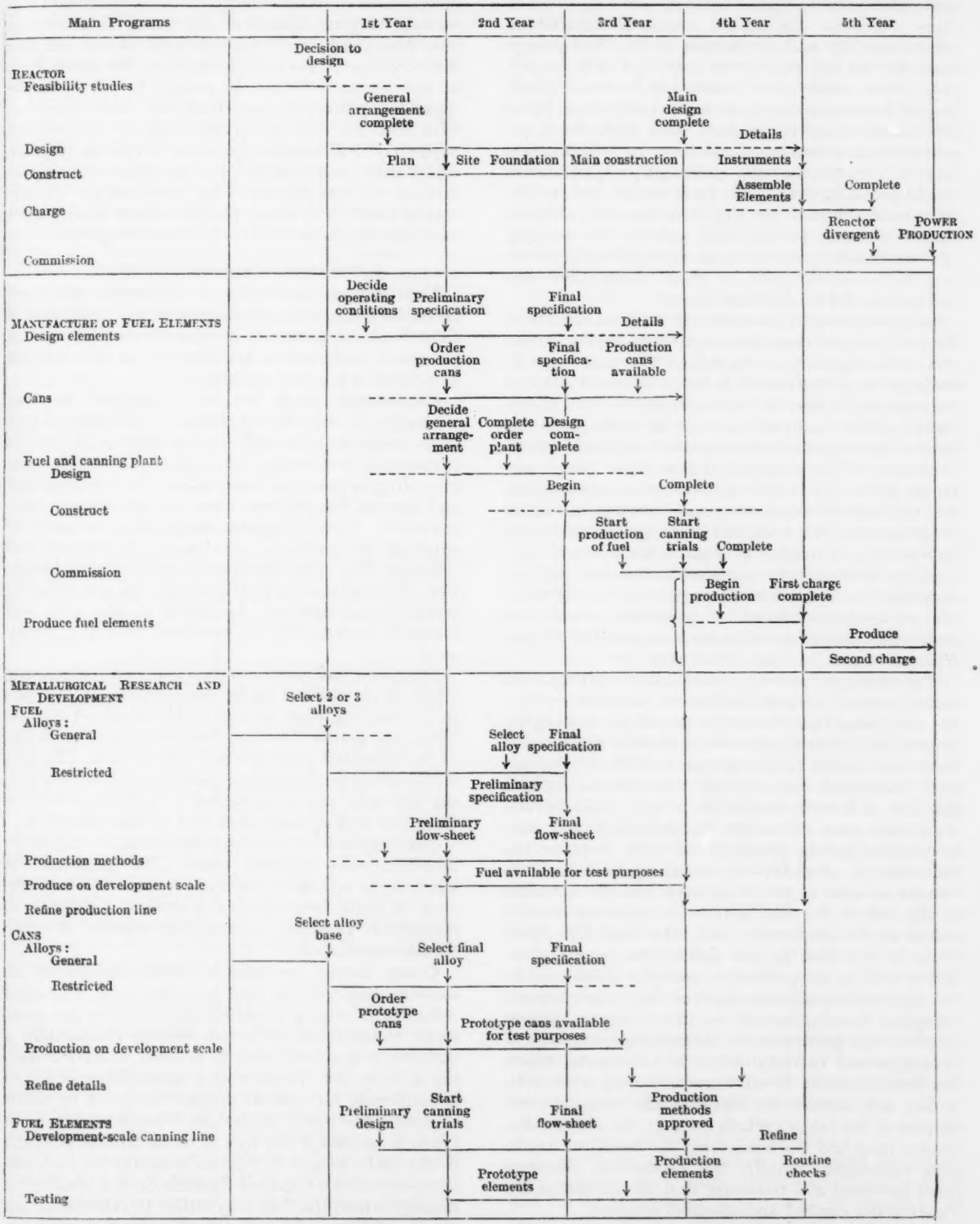

Figure 3. Bar-Line Chart Illustrating the Fuel-Element Time-Table for a Hypothetical Nuclear-Power Reactor.

assembled from scratch, it is hardly too long to allow three years for the design, ordering, installation, commissioning, and production of the first charge ready to load into the reactor at the end of the fourth year. Cans made from more conventional alloys should be ordered so as to be in production about six months ahead of the fuel. Cans made from unconventional alloys may call for a new production line, in which case the preliminary specification would probably need to be fixed rather earlier. The time scale adopted for Fig. 3 necessarily requires that flow-sheets for the fuel and for the canning operations are complete in all except details at the end of the second year, i.e. three years before the full production of electrical power.

The research and development work on the alloys for the fuels and cans also must reach fruition at the end of the second year, therefore. The technique invariably is to start with a range of materials and successively to narrow down the choice until the final alloys for fuel and can may be selected on the basis of the accumulated available information. Concentration of the experimental work on fewer materials allows production methods to be investigated, and the scale of the development work is increased progressively. The fuels and canning materials must be tested as thoroughly as possible for compatibility, stability at temperature and under thermal cycling, resistance to irradiation damage, mode of deformation at service temperature, grain-size, response to heat-treatment, effect of impurities, possible surface treatments and by many other tests.

The making of prototype cans calls for all the tests to be repeated on semi-production material, so that the completed fuel element is proved as thoroughly as possible and nothing is left to chance which could have been tested before operation of the reactor began. Additional tests include heat-transfer and, if possible, full-scale irradiation trials, while special equipment may be needed for metrology and non-destructive testing. Development-scale work on the fuel-element assembly—or "canning line"—will be started as soon as prototype cans become available at the end of the first year, some eighteen months ahead of the production cans. The final flow-sheet must be specified by the end of the second year. Every step in the production must be considered in the light of the service required from the element. Intensive development of manufacturing techniques involves the production of increasing quantities of prototype and pre-production fuel elements, which are then available for numerous proving trials both within and outside the metallurgical program; examples of the latter include tests on the charge/discharge gear and the equipment for handling irradiated cartridges. Finally, the production elements must be tested also to ensure that all operations are yielding the desired and specified product.

It will be realized that every aspect of the main project must be dealt with on the same principle of controlled and scheduled development, if electrical power from nuclear energy is to be produced according to plan. Chemical processing involves not only the extraction of uranium from the ore, but also the recovery of the plutonium from the spent fuel, so that plants will later be needed to put back the separated plutonium into fuels for other reactors. This does not fall within the scope of the present paper, nor will mention be made of reactor physics, which may need metallurgical assistance in the production of fuel elements for zero-energy experimental reactors to check the theoretical calculations on which the power reactor has been designed.

LABORATORY-SCALE INVESTIGATIONS

Metallurgical research on a laboratory scale may be exploratory, and concerned with the collection of data. Such research may involve the development of processes and special instruments or the routine examination of small samples.

Exploratory work has to be carried on continuously. Compatibility tests of different alloys with uranium under different conditions of surface preparation and environment may fall into this category. In practice small samples are clamped together and heated for various times at appropriate temperatures. Metallographic examination is used to establish the presence or absence of reaction and diffusion. The upper limiting temperature for formation of eutectic or a brittle compound for different pairs of materials can be found in this way and means of suppressing the reactions sought, if necessary.

Oxidation and corrosion tests are made on canning alloys in the coolant under the conditions to be met in service, e.g. with coolant of the expected composition and normal freedom from entrapped particles, at the expected pressure and rate of flow. The aim is to explore promising can materials and to establish the life than can be expected as a function of the thickness and surface treatment of each material.

The response of uranium and uranium alloys to heat-treatment requires study. The grain-size of uranium is not easily measured, because the presence of quite large subgrains makes it difficult to distinguish between neighboring crystals of very similar orientation.

Creep testing provides a good example of an experimental method used to collect data. The chief difficulty in testing uranium alloys lies in the reactivity of the metal. It is not possible to maintain a sufficiently good vacuum to prevent oxidation during a creep test. A protective atmosphere of argon is employed, but special precautions must be taken to ensure the purity of the gas.[13] Some resistance to creep is needed if the fuel is to contribute strength to the fuel element. If the can supports the fuel, the creep-resistance required depends on the irradiation damage which the fuel may suffer in relation to the stresses this would impose on the can. For example, a fuel liable to growth under irradiation but soft enough to be deformed by the can, might be pre-

ferred to a fuel suffering little growth under irradiation but strong enough to impose severe strains in the can. Creep tests have to be carried out on canning alloys also, preferably in the coolant to be used in the reactor.

Examples of the laboratory-scale development of manufacturing processes may be found in powder metallurgy. For instance, the sintering of refractory metals such as niobium and vanadium is not straightforward if the finished product is to be ductile. These metals are very reactive, and partial pressure of oxygen and nitrogen must be extremely low if embrittlement is to be avoided. If the sintering is carried out in vacuum, the pumping rate must be high and the leak rate extremely small. Sintering may be by either high- or radio-frequency heating or by direct heating. The methods must be established on a small scale before large equipment is installed.

Arc melting by either non-consumable or consumable electrode units is being developed for higher-melting-point metals such as molybdenum, vanadium, zirconium, and thorium, and for uranium alloys. Equipment must be provided to control the arc voltage to a given value and automatically to strike and to locate the arc. Ion bombardment can be used to accelerate degassing.

Routine examination is required for all materials and at each stage in the fabrication of fuel elements; powdered metals must be checked for their gas contents; canning materials must be checked for inclusions.

The routine examination of uranium-base alloys for fuel elements frequently includes the microscopic measurement of grain-size. The inspection requires an appreciable number of operatives, and a rapid non-destructive test for grain-size would be of considerable value, while in addition a much more thorough examination would be possible.

Experiments have shown that the grain-size of a metal has a considerable effect on the attenuation of ultrasonic waves, and this property can be used to assess grain-size.[14] Experimental work is in progress to apply the technique to uranium. The relative attenuation of the ultrasonic wave was determined by counting the number of multiple reflections from the distant face of the specimen.

DEVELOPMENT-SCALE INVESTIGATION

Metallurgical work on a development scale may involve the working out of processes, may establish fabrication and testing methods for each stage in the manufacture of fuel elements, or may be concerned with the production of prototype fuel elements for test purposes. The scale of operation has to be fairly large, since production methods will be based on the results, and the testing must be sufficiently thorough both to provide and to check design data. Operational research methods and statistical analysis of the results are necessary to ensure the maximum of reliable information from the minimum of experimental effort. A few typical examples are described very briefly below.

The development of special processes may involve the fabrication of uranium by rolling or extrusion. Special care must be taken in handling uranium to avoid ingestion, because of the poisonous nature of the oxide. Extrusion may be carried out in sealed cans—made, for instance, of copper or zirconium—which may be stripped off later, if necessary. Rolling is possible in the same way, or by the use of an adherent and continuous film of salt, which prevents uranium oxide from being thrown into the atmosphere. This technique may be combined conveniently with salt-bath heating.

Long-term heating of cast bars may lead to severe distortion because of release of internal stresses resulting from variable cooling conditions in the mold. These stresses have a complex distribution, and heat-treated bars are much to be preferred, being more stable because the internal-stress distribution is symmetrical. Heat-treatment, however, causes dimensional changes, which appear to vary according to the purity of the metal. Certain impurities have the effect of reducing the amount of distortion which occurs on heating. It will be appreciated, therefore, that the control of dimensional variations in uranium bars is particularly important when the bars are to be enclosed in cans before use in the piles.

Sealing of the can may be effected by welding. A convenient method is to drop a flanged lid into the end of the can and weld together the adjoining rims. Fully automatic argon-arc welding has been used. The welding machine incorporates a motor-driven shaft carrying cams which operate micro-switches governing all the operations. The can remains stationary while the argon-arc electrode circles the top, making the weld without any filter rod. The optimum welding conditions were established by a series of factorial experiments. It was important to establish statistically the depth of penetration in order to ensure that an adequate thickness of weld metal was available as a protection against leaks. Twenty-four microsections were prepared from each of a number of welds of adjacent upstanding rims, each 0.060 in. thick. Statistical examination showed that the chance of finding a weld depth of less than 0.030 in. was about one in a thousand. It was also confirmed that the welds contained no local regions of small weld depth.

Fuel elements in which the uranium is sealed in a can must clearly be tested for leaks at appropriate stages in their fabrication, and special techniques have been developed for this purpose.

IRRADIATION TESTING

To irradiate under closely controlled conditions may involve appreciable engineering design effort and the construction of large pieces of equipment. In order to subject the specimens to the required neutron flux, they may have to be placed 30 ft. inside a pile, so that fairly massive charge and discharge gear

must be set up at the working face of the reactor. It is good practice to control the temperature at which irradiation is being carried out; furnaces must therefore be provided to maintain the temperature when the pile is not operating, so as to avoid thermal cycling. On the other hand, a coolant must be employed to restrict the specimen temperature when the pile is operating. It is normally simpler to maintain a constant flow of coolant at all times and to make the furnaces sufficiently powerful to keep up the temperature when the pile is shut down. Power, thermo-couple, and control leads must be brought out from the pile in such a way as not to restrict the coolant, while the specimens are placed in special canisters of known heat-transfer characteristics. A high rate of burn-up is usually sought, involving the use of enriched fuel. For this reason the neutron penetration may not be very deep, so that the specimens often will be fairly small. The experiments are costly in money and effort and therefore must be very closely planned. The specimens must be examined very carefully before test for dimensions, density, microstructure, and also examined as thoroughly as possible after irradiation. Special remote-handling equipment almost certainly will be called for; while the irradiation to which the specimens have been subjected must be assessed. A large number of out-of-pile tests will be conducted also on closely similar materials.

Larger bars, such as full-scale fuel elements, must be irradiated at both fluctuating and constant temperature, but in this case the lower rate of burn-up must be accepted. Less rigorous tests can be carried out under the temperature conditions at which the pile is operated, and much useful work can be done in this way.

The need for means of irradiation testing has prompted the construction of high-flux reactors with special facilities for experimental work, such as loops through which chosen coolants can be circulated at the desired temperature. The DIDO reactors under construction at Dounreay and Harwell are intended to serve this purpose and to provide a high neutron flux of 10^{14} neutrons/sec./cm.^{2} with heavy water as the coolant.

FUEL-ELEMENT PERFORMANCE AND COST OF ELECTRICITY

The properties and behavior of the fuel element affect the cost of electricty in two ways: by their influence on the capital cost per kilowatt hour despatched and by their influence on the operating costs.

The capital and overhead charges account for a higher proportion of the cost of the electricity from a nuclear-power station than in the case of that from a coal-fired power station. Therefore the production of fuel elements which significantly raised the overall efficiency of electricity generation from nuclear energy (i.e. net electrical output/heat liberated in reactor) would have a correspondingly large effect on the cost of electricity sent out. This could be achieved by a fuel element which allowed the exit temperature of the coolant to be raised, because an increased steam temperature would lead to increased efficiency in the generation of electricity.

The annual operating costs include charges for personnel and handling, and for the replacement of the fuel elements, less the credit for the production of plutonium. The life of the fuel elements probably does not have much influence on the charges or on the rate of creation of plutonium. However, the replacement charges are inversely proportional to the fuel-element life, so that the cost of electricity generated from nuclear energy will depend largely on achieving a reasonable life from the fuel elements. Research and development on fuel elements must therefore aim at higher operating temperatures and increased life under irradiation, complete reliability, and ease of fabrication. Satisfactory solutions to fuel-element problems must be provided also on the appropriate dates in the construction program of each power reactor.

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NAVAL ENGINEERING IN THE ROYAL NAVY

ACKNOWLEDGEMENT

This is an abridged version of a lecture delivered in London on 28 January 1956 by Vice Admiral Sir Frank Mason, Engineer-in-Chief of the Royal Navy. It was published in the June, 1956, edition of "The Chartered Mechanical Engineer."

THE RESPONSIBILITIES OF THE ENGINEER-IN-CHIEF OF the Fleet, which is the office I hold, have grown more varied as the engineering applied to warships has become more diverse and complex, so that they are not easy to describe. He deals with the training, appointing and promotion of all officers and ratings of the Branch for the varied fields which they cover; his responsibility for materiel is confined to the propulsion machinery and auxiliary machinery of H.M. Ships only. Engineer officers, for whose training and careers he is responsible, cover much wider fields which can be grouped under ordnance engineering and aeronautical engineering. For each of these fields the phases of research, design, development, production, maintenance and repair are all covered by engineer officers. In addition, they are required for the training of officers and ratings, for liaison staffs abroad and with other services, and as assistant naval attaches in foreign countries.

THE ENGINEERING BRANCH

It should perhaps be made clear straight away that engineer officers in the Royal Navy are primarily naval officers dealing with a large body of men (approximately 15 per cent of the total naval manpower) and, although their engineering ability is vital to the future of the nation's defense, it is complementary to the primary function of leadership. This leadership cannot, however, be exercised without adequate technical knowledge and experience.

TRAINING AND EMPLOYMENT OF ENGINEER OFFICERS

Although the division of material responsibility between the various departments is clearly drawn, the officers, as individuals, are not rigidly confined to one sphere. The object is to produce officers in the senior ranks who can administer any of these divisions of engineering. For instance, there is nothing to prevent an officer who has spent most of his life on ordnance equipment having a senior post on the marine propulsion or the air engineering side.* This versatility, which is very necessary if the Royal Navy is to make the best use of its officers and to attain a proper cohesion of the different specializations, is achieved primarily by a thorough basic training in engineering.

After entering at eighteen the cadets, who are the main source of officers, spend two years at the Britannia Royal Naval College, Dartmouth, learning, with their contemporaries from other branches, the basic workings of the various branches of the Royal Navy, such as seamanship, gunnery, torpedoes, communications and engineering. Part of this is done at sea, and after a further period at sea to obtain a certificate of competence the officers qualifying in engineering go to the Royal Naval Engineering College, Manadon, for two years of training in basic engineering followed by a year in one of the specialized branches of marine, ordnance or air engineering. In this year they are joined by officers of under twenty-five years promoted from artificer.

Officers then go to sea or to air stations. They are employed mainly in their specialist capacity until about the age of forty-five, returning to sea periodically.

The duties performed by engineer officers in the air specialization include: test pilots; air armament experts; maintenance engineer officers for aircraft of a squadron, aircraft carrier or air station; or charge

*Since the publication of the new officers structure for the Royal Navy a variety of senior administrative posts outside the engineering specialization will be open to senior officers of wide engineering qualifications.

of an aircraft repair yard where aircraft and their engines are repaired and reconditioned.

The ordnance engineering side covers development, design, production, maintenance and repair of the whole of the mechanical equipment for loading and controlling guns, anti-submarine weapons, guided missiles and torpedoes.

Marine engineering in the Navy covers a wide range of equipment besides the main engines of ships, submarines and small craft; catapults; organization and training in damage control to keep ships afloat and moving after damage; refrigerators and most of the ships' services.

The functions performed range from direct development work at the Admiralty Fuel Experimental Station at Haslar, to design in the Admiralty, overseeing at firms and shipyards, or repair in Dockyards.

ADVANCED ENGINEERING COURSE

A number of officers is selected to undergo postgraduate training at the Royal Naval College, Greenwich. This is devoted to higher mathematics, applied mechanics, metallurgy, design and experimental work, which should fit them, in conjunction with their sea experience, to give the necessary guidance to industry in the development of naval machinery.

ROLE OF THE USER

Probably the greatest need in modern developments is for good engineering. The scientist, presented with a problem, produces a possible solution. The task of making that solution a workable reality depends on understanding not only the original problem and the basic solution but also all the intricate details of daily use to which the equipment will be put. In fact, I do not believe that it is possible to design the best equipment for a ship or for any other purpose without the guidance of the man who uses and maintains it, provided, of course, that he has the experience and training to qualify him to give that guidance constructively.

NAVAL ENGINEERING PROBLEM

The particular problem which faces the designer of naval machinery is to reduce to a minimum the weight and space occupied by the machinery and its fuel, while keeping it as simple as possible for ease of operation and maintenance. The problems are different and generally more severe than those met with in the design of power-station or merchant-ship machinery. Not only is a reasonable efficiency necessary at full power in order to reduce the size of boilers, pumps, pipes and valves, but also a very high efficiency is required down to below one-fifth of full power to give the ship maximum endurance for a minimum of fuel at the normal cruising speed. The machinery and fuel weight adds up to a considerable percentage of the total ship's displacement, so that in general anything that is saved can be added to the fighting equipment of the ship.

Another aspect which adds to the difficulty of naval design is the very great care which must be taken to make the machinery proof against shock. In fact it must be designed so that it can withstand loadings of many times its own weight under shock accelerations from underwater explosions.

RESEARCH AND DEVELOPMENT

Since the war a great deal of money has been spent on research and development to overcome these difficulties. This work is done mainly under contract by firms best fitted for it and our aim has always been to make the fullest use of the knowledge and ability in the whole of British industry.

It was decided that, after the 1939-45 war, much greater latitude should be allowed in the use of alloyed and other special materials, and it was accepted that machinery would need to be built to greater accuracy, and run at higher speeds. This decision meant that many parts and even complete engines, which formerly could be kept serviceable by jobbing repairs, must now be replaced by new ones on the completion of their stipulated life. It followed that standardization had to be introduced wherever possible, together with a greatly improved system for the world-wide supply of spare parts and units. It will be seen that the Royal Navy is getting nearer the conception as in aircraft of repair by replacement, although it is unlikely that we shall ever approach the completeness with which this system is applied to the airplane, except perhaps in the small and very specialized craft to which it is akin.

TYPES OF MACHINERY

The types of machinery which have emerged as the result of this policy cover all classes of ship. In aircraft carriers, which have to be capable of frequent bursts of high power for flying operations and use the greatest power per shaft, geared steam-turbine machinery still reigns supreme. In cruisers and destroyers again it is primarily steam-turbine installations, but considerable work is going forward on the possibility of using gas turbines geared to the same shafts for boosting the full power of the steam installation. Since these classes of ship spend a comparatively small proportion of their life at high power, fuel consumption is not so important as it is at lower speeds, and it is possible by using the simple gas-turbine cycles to produce a great deal of power in a small space.

There are, of course, many problems, such as, for example, the size of the air ducts required, which is particularly important in larger ships where these air ducts have to be taken through several decks. Even for smaller ships there is considerable difficulty in fitting all the fighting and navigating equipment of a warship into the space on the upper deck and large funnels and air intakes are, therefore, unpopular. However, as gas turbines are developed to use higher temperatures and as efficiencies improve, these difficulties will progressively diminish.

For smaller ships, where the power on each shaft is below about 8,000 h.p., Diesel engines offer advantages. The normal merchant-ship Diesel engines are far too large and heavy for naval purposes and we have, therefore, devoted considerable effort to developing small high-speed, light-weight engines. The provision of spare parts for these all over the world is a major consideration and we try, therefore, to use engines with a standard design of cylinder unit for a large range of powers using anything from six to sixteen cylinders. For small high-speed craft, gas turbines are already proving their worth and we have three boats at present under trial where gas turbines are being pitted against the latest light-weight Diesel engines.

In submarines, Diesel machinery has reigned supreme for many years and the improvement of this type of machinery continues but, as you may be aware, we are also experimenting with submarines whose high underwater speeds are produced by engines using hydrogen peroxide. This produces the oxygen required to burn fuel as well as giving out intense heat as it breaks down into oxygen and steam, so that the submarine is independent of atmospheric air.

THE RESULTS OF RESEARCH AND DEVELOPMENT

That is the general picture; and now I should like to tell you something of what we have secured for our money.

Steam

In the sphere of steam, we have more than doubled the fuel burning heat release rate in boiler furnaces since the 1939-45 war. We have introduced superheat control so that the benefit of using higher steam temperatures is obtained at low as well as at high powers. This also enables us to protect the machinery from the worst conditions of thermal stress during maneuvering.

Other methods of saving weight and space include the use of double-reduction gears with alloy steel turbine rotors, reducing the size of the turbines and hence enhancing reliability under high steam conditions; improvement of gear production methods and the introduction of hardened and ground main gears; the development of auxiliary turbines running at over 20,000 r.p.m. and the use of epicyclic gearing. These and similar developments have given an overall reduction of about 30 per cent in the weight of machinery designed since the 1939-45 war.

Development Teams

An essential part of meeting these needs has been played by design development teams set up to study the best way of meeting our requirements in various fields under development contracts. These have involved searching for the best that Britain can offer in any field and choosing the best answer for any application by knitting together various components into the most suitable overall installation.

Diesel Engines

In the field of Diesel engines, two engines in particular have emerged. One is the Admiralty Standard Range I engine for normal applications of high-speed Diesel engines, particularly where ease of maintenance in place is required. This engine can be built up to sixteen-cylinder, supercharged V-engines of about 2,200 h.p. down to a six-cylinder, normally aspirated, in-line engine of 525 h.p. A high proportion of the parts are standard for the whole range, and maintenance problems have received detailed study.

The other engine developed particularly for naval purposes is the Deltic engine. It is of very light weight and is designed for applications where the engine can be lifted out for refitting.

A commercial Diesel engine has also been adopted as the Admiralty Standard Range II engine after additional development to improve its reliability and ease of maintenance and reduce its magnetic signature.

Diesel engines of smaller power for motor boats, emergency pumps and so on are continually under test at the Admiralty Engineering Laboratory, West Drayton, to find their weaknesses and help the makers to improve them before and after their adoption by the Royal Navy.

Gas Turbines

The developments for the Royal Navy in gas turbines have received fairly wide publicity already and you probably know of the Motor Gunboat 2009 which was driven by the first seagoing gas turbine in the world. Since this, we have installed gas turbines in two other high-speed coastal craft, H.M.S. *Bold Pioneer* and H.M.S. *Bold Pathfinder,* which have Diesel engines for cruising and gas turbines for high speed. We now have H.M.S. *Grey Goose* at sea with an advanced gas-turbine cycle which gives it good efficiency over a wide range down to below 20 per cent of full power. This needs no separate cruising engine and is the first seagoing gas turbine fitted as the sole means of propulsion.

From these sea trials we learn a great deal which gives us encouragement in the application of gas turbines for higher powers. One of the major lessons has been that the difference between the requirements for aircraft gas turbines and naval gas turbines is such that they are seldom interchangeable. The wider range of speed, the external vibration, the salt spray and the need for a somewhat longer life than is normal in aircraft practice make it essential to test engines afloat before any estimate can be formed of their reliability under naval conditions. It is, therefore, preferable, although expensive, to have engines designed from the beginning for the duty they are to perform at sea. Where gas turbines developed for aircraft can be used for naval purposes, however, we shall do so.

We have also had developed some successful smaller gas turbines for electric generators and other applications.

Steam Catapults

Probably, the development which has gained the greatest recognition is the steam catapult. This has been adopted by the American, French, Dutch and Commonwealth Navies. Nations, like individuals, learn if they are wise from the experience and techniques of other nations and it is well that we can repay, in major kind, some of the inspiration we have gained, particularly from the United States of America.

Automatic Control

Automatic control is already being applied to machinery to meet the needs of future methods of warfare. As machinery becomes more complex and more highly forced to reduce weight and space, a higher degree of automaticity will also be needed to ensure that the machinery is operated in the way in which the designer intended.

The Law of Diminishing Returns

We are competing with a law of diminishing returns in raising steam conditions, so that although they will undoubtedly continue to rise in the future this is likely to be a fairly slow process. Probably, our best line, therefore, will be to use gas turbines in combination with steam turbines for high powers. For low powers we have a choice of light-weight Diesel engines where economy of fuel is particularly important and simple gas turbines where weight is the predominating factor. There is also the possibility that free-piston gas-generators in combination with a gas turbine may show gains over Diesel engines at the low powers.

THE FUTURE

Nuclear-reactor design is only in its infancy, but investigations to date indicate that power from this source has enormous possibilities and may ultimately displace, in most applications, other types of heat producer.

From a naval point of view the main, and perhaps only, advantage of nuclear power lies in the fact that with its use fuel and fuel stowage would no longer be a ship-design problem and the nature of the logistic problem would be radically altered. Endurance would be practically unlimited by our present standards and the speed at which fleets could move would no longer be restricted by the necessity to conserve fuel. We can, therefore, expect the whole tempo of naval movements to speed up; and the ship designer will be set a new problem to design hulls to withstand high speed in rough seas continually.

To achieve results from nuclear energy great effort must be devoted to development.

We have come from oars to sail, sail to steam, coal to oil, and now we seem to be at the beginning of another era using yet another source of power, even if in the early stages that power is likely to be applied by conventional means.

Plans are underway for the building of a plant in India for the construction of Diesel machinery. The plant will be located at Vizagapatam, where the largest Indian shipyard is located.

WILLIAM GRAY BEYER

AUTOMATIC CONTROL FOR THE BEGINNER

THE AUTHOR

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This paper was written as a seminar report in an undergraduate course in instrumentation and control at Drexel Institute of Technology. A graduate of Drexel's Evening College, the author is currently working toward a Master's degree at the Institute. He is also a member of the A.I.E.E. and the I.S.A.

INTRODUCTION

BEING A NOVICE in any expanding field of endeavor is always difficult. This is so because there is seldom any clear-cut, "all-in-one-place" statement of the fundamentals of the given field. It's also true of almost every phase of engineering; and particularly true in the field of automatic control. It is the purpose of this paper to present a condensed, easily assimilable explanation of those phases of automatic control which are basic to an understanding of the more advanced work being done in this rapidly widening field. And since a major difficulty for the beginner in automatic control work lies in learning the "language" used, this paper is logically concerned with defining those terms which are basic.

THE CONTROL LOOP

The foundations of automatic control have been built up around an ideal control system, the so-called *control loop*. This is shown by means of the block diagram, figure 1. Those portions shown dotted are elements which may or may not be present depending on the make-up of the specific loop.

The process is the "heart" of any automatic control system. It refers to a given aggregate of functions being performed on and by one set of equipment. For example, heating your home by means of a hot-air system and an oil burner is a familiar "process." Here the "aggregate of functions" consists of burning oil to heat air which in turn circulates about the house. The "equipment" in this case is the oil-

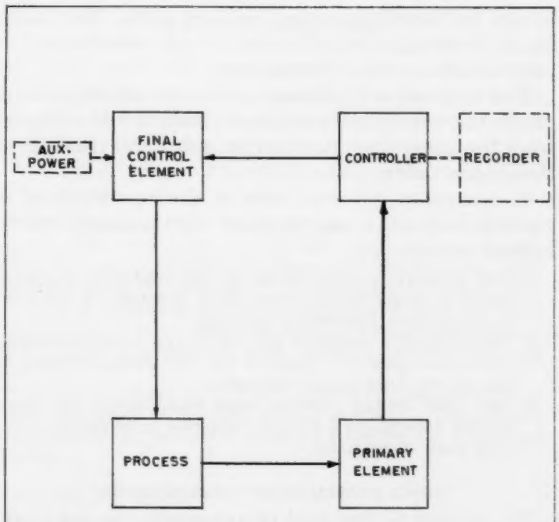


FIG. 1
CONTROL LOOP

Figure 1. The Control Loop.

burner and the air ducts used in circulation. Two easily recognized examples of industrial processes are the making of steel in an open-hearth furnace, and the pasteurizing of milk in steam-jacketed kettles.

In every process, the *controlled variable* is the quantity or condition which is measured and controlled. In the above example of pasteurizing milk, temperature is the variable which is controlled in order to produce the desired result—killing germs and bacteria. The variable to be controlled will depend on the individual process. Some other common examples are flow, pressure, level, and pH.

The *primary element* is the device used to measure the value of the controlled variable. Its function is to transmit to the controller a signal which is in some way proportional to the value of the controlled variable. Typical primary elements are thermocouples, resistance thermometers, radiation pyrometers, flowmeters, pH electrodes, etc.

The Controller is the device which compares the value of the controlled variable to some preset reference value; and operates to correct any deviation of the variable from the reference. This "preset reference value" is usually referred to as the "set point."* Again using the hot-air oil burner system as as example, the controller is the wall-mounted thermostat. When the room temperature drops lower than the manually set reference, the contacts attached to the bimetallic element "make" a circuit which initiates action by the oil pump and related parts. This making or breaking of an electrical circuit constitutes the control action of the thermostat.

The final control element is the unit which manipulates the controlled variable in response to a signal from the controller. A common industrial element is the control valve.

In summary, we can look at the operation of a control loop as a sequence of continuously interrelated events:

1. The primary element sends to the controller a signal which is proportional to the value of some one variable in the process (controlled variable).
2. The controller compares this value to a preset reference value (set point). If there is any deviation, a signal is sent to the final control element.
3. The final control element then manipulates the controlled variable in a manner designed to bring the variable back to set point.

SOME PRELIMINARY ASSUMPTIONS

The novice in the field of automatic control is always confronted with the problem of differentiating between basic modes of control and specific controllers which do the job. Inevitably, one's background and experience will associate a particular device with a given manner of control. As a result, confusion develops in distinguishing controller from control action. In defining and discussing the various types of control action, this confusion can be avoided if certain arbitrary assumptions are made. For purposes of discussion in this paper, the control-loop will be visualized as being composed of:

1. Process—thermal-type; consider temperature to be the controlled variable.
2. Primary element—a thermocouple.
3. Controller—a potentiometer type recorder-controller with (or without) an associated electronic control unit.
4. Final control element—a motor operated valve.

The beginner can thus use the above components to illustrate for himself any of the modes of control which will be discussed. Further, the diagrams can be visualized as the ideal record drawn by a single point strip chart recording instrument. The above assumptions are, however, merely a convenience. The definitions are applicable to any combination of process and control equipment.

MODES OF CONTROL

The principal modes of control to be considered are:

1. Two position control.
2. Floating action.
3. Proportional action.
4. Proportional plus reset action.
5. Proportional plus reset plus rate action.

It must be stressed that these modes are by no means the only possible types of control action. They do, however, represent the overwhelming majority of control applications currently in use. Further, an understanding of the above modes is basic to the understanding of any type of control action.

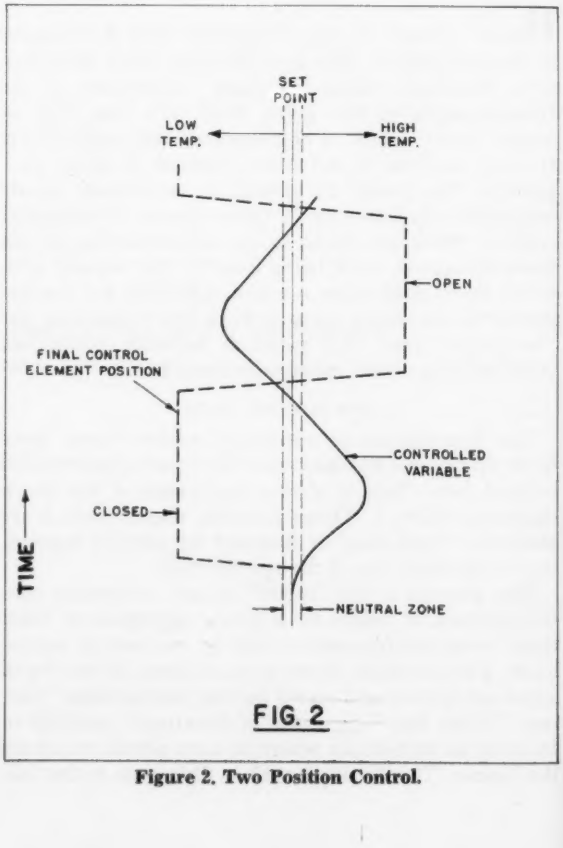


Figure 2. Two Position Control.

*Common parlance often makes use of the expression "control point" in this connection, although this is not entirely correct.

Two Position Control (off-On Control)

This can be defined as:

A mode of control in which any departure from set point by the controlled variable causes the final control element to move from one extreme position to the other.

In brief, if the variable is above the set point, the final control element is fully closed; and vice versa. This is illustrated in Figure 2.

The neutral zone shown in the figure may or may not be present, depending on the type of controller. It can be defined as:

That range of values of the controlled variable for which no change in position of the final control element occurs.

Thus, a 2% neutral zone would mean that the variable could move away from control point by 1% of scale before the value would run to its limit.

Using the strip chart recorder to give two position control can be accomplished with limit switches actuated by movement of the pointer from control point. The neutral zone can be adjusted to any desired value.

Naturally, there are hundreds of other devices which will give two position control, probably all cheaper than a strip chart recorder. The bimetallic thermostat is typical of the multitude of simple control devices now on the market.

Two position control is normally used on processes with large thermal capacity, or quantity (a large vat, for example). On such processes, the "off-on" control action will not cause large fluctuations of the variable about control point.

A common type of two position control is the so-called *Throttling Two Position Control.* This differs from the above only in that departure from control point moves the valve to some partially open or closed position. This is used to reduce the magnitude of the variable's deviation from control point due to full off-on action. As with simple two position action, a cycling about control point is always in evidence. The throttling action only tends to reduce the amplitude of the departure. Naturally, this can be used only in cases where maximum demand (fuel requirement) falls between the limits set on the final control element.

Floating Action

Floating action is widely used in modern control devices. It can be defined as:

A mode of control in which deviation of the controlled variable to either side of a neutral zone causes the final control element to move gradually in one direction until the controlled variable has returned to the neutral zone.

This is shown diagrammatically in Figure 3.

The definition applies specifically to that form of floating action which is often referred to as "single speed floating with neutral." This type of action is, however, common to the great majority of control devices in the floating action class. The outstanding feature of this mode is that the final control element "floats." That is, it has no fixed position with respect to the value of the controlled variable. Floating action will normally employ a slower stroking valve

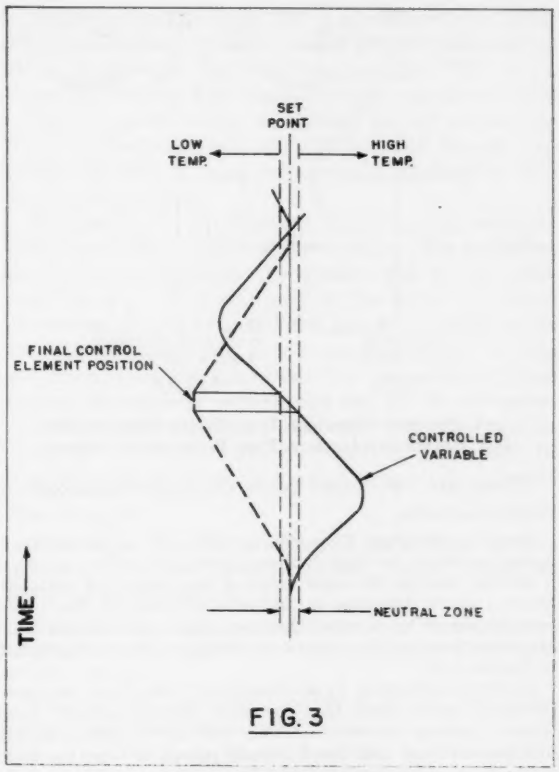


Figure 3. Floating Action

than that used with two-position control. Although it will give much better control of a given process than the two-position type, it also is characterized by cycling about the set point.

Two other forms of floating action which are often encountered are:

Multi-Speed—In this mode, the final control element is moved at one of two or more speeds, each of which corresponds to a given range of deviation from the set point. With such an action, for example, a temperature deviation from set point of from zero to five per cent would cause the valve to move at one speed; and a deviation of five to 15 per cent would cause the valve to move at some greater rate, and so on.

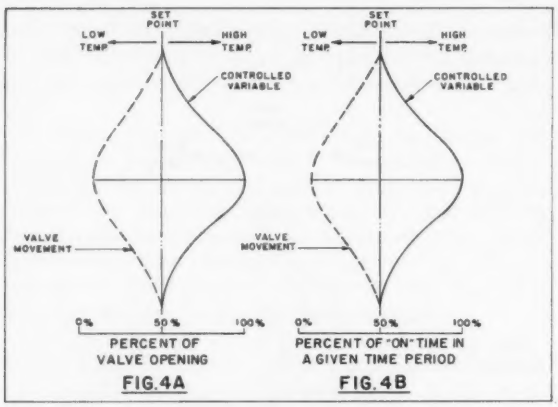
Proportional Speed—The distinguishing feature of this mode is that the speed of the final control element is proportional to the amount of deviation from set point by the controlled variable.

Proportional Action

This is defined as:

A mode of control in which any departure from set point by the controlled variable is accompanied by a proportional change in the final control element.

For each value of the controlled variable there will be one definite value of the final element. Thus, if temperature should move off control point, the valve will be moved to some new position. And since for each value of the controlled variable there is a corresponding final control element position, the amount of valve change will be proportional to the amount of deviation.



4-A. Position-Adjusting-Type Proportional Action.
4-B. Duration-Adjusting-Type Proportional Action.

There are two main types of proportional-action control devices.

Position Adjusting Type—These units give a proportional action in which the final element (such as a valve) assumes a definite position for each value of the controlled variable. Here, a given deviation in temperature will run the valve open or closed to a certain position. Again, this position will be proportional to the amount of deviation. This is illustrated in Figure 4-A.

Duration Adjusting Type—Devices of this class use proportional action such that the final control element (e.g. electric heating elements) is held "on" for a definite period of time and then "off" for a definite period of time, for each value of the controlled variable. This is shown in Figure 4-B. Note that the abscissa values on the final element are in "per cent 'on' time *in a given* time period." This means, for example, that with a wide temperature deviation, the heating elements of an electric furnace might be "on" for 50 seconds out of every minute. Electrically heated furnaces are typical of duration-adjusting-type applications.

It is well to note that proportional action generally marks the dividing line between "simple" and "complex" controllers. The devices used to give two-position and floating action control are usually simple, inexpensive devices having only a few electrical components. The controllers designed to give proportional action usually involve a more complex system.

No discussion of proportional action would be complete without consideration of the important concept of *proportional band*. A given proportional band is that percentage of the range of the controlled variable which corresponds to 100% of the final control element's range. It is the ratio of the movement of the valve to movement of temperature.

Referring to Figure 5, we can see that a proportional band setting of 20% means that a 20% movement of the variable will move the valve from full open to full closed, or 100% of its travel. It is the proportional band setting which enables us to adapt proportional action to a particular process. For example, where it is desired to control a high thermal capacity process within close limits, a very narrow proportional band would be used. This would mean that a small deviation from set point would result in a large amount of heat being added to the process. A pH process, on the other hand, which can have large inherent "swings" away from set point will often use proportional band settings of 150% or more.

Reset Action

In modern automatic controllers, reset action is used in conjunction with proportional action. As such, it can be defined as:

A mode of control which reacts to changes in load by gradually shifting the proportional band up or down the range of the controller until the controlled variable returns to set point.

This mode is also referred to as "reset response." Figure 6-A shows the movement of the control valve if proportional action were working alone. Assuming that a sustained change in load causes a deviation, reset action alone would move the valve as shown in Figure 6-B. Figure 6-C, then, shows the resultant motion of the valve in response to linear load change when proportional-plus-reset action is used. The "plus" serves to indicate that this "resultant" action is the algebraic sum of the two control actions.

From the viewpoint of what is happening to the proportional band, Figure 7 illustrates the action of reset when a linear change occurs. The value of reset as a corrective measure against deviations is shown by the fact that at the end of five minutes, the valve is only 15% open. Had no reset action been present, this figure would more likely have been about 45%.

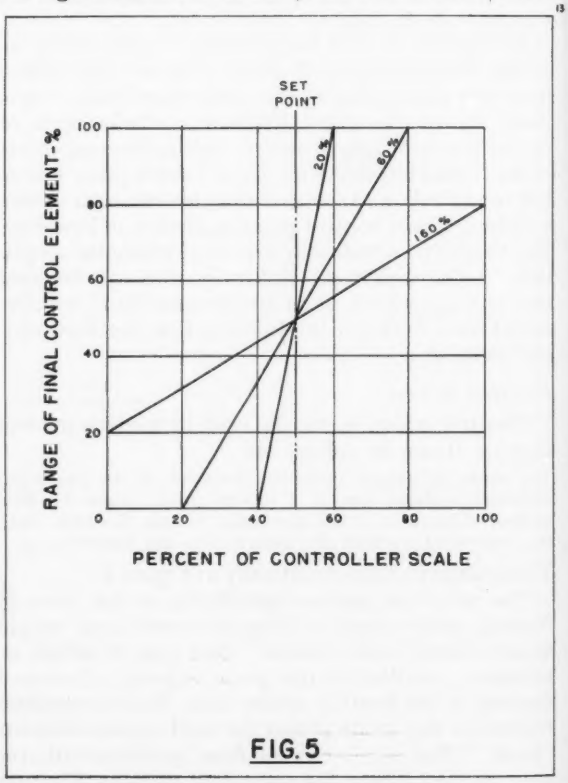


Figure 5. Proportional Bands.

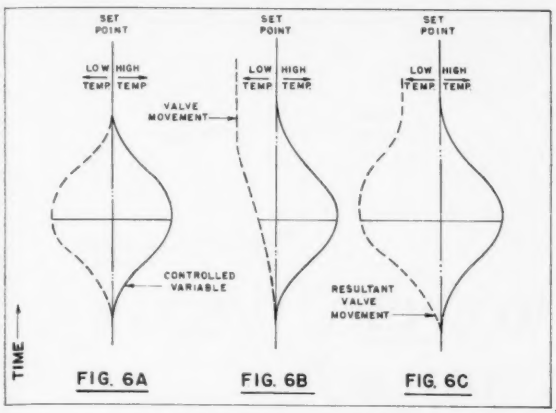


Figure 6-A. Proportional Action
Figure 6-B. Reset Action
Figure 6-C. Proportional Plus Reset

Reset has particular value on those processes where changes in load or demand are a problem to control. In such cases, the proportional action provides stable control action, while the reset action takes care of the "offset" of the variable due to the load change.

The measure of reset action, called "reset rate," is commonly expressed as "repeats per minute." This term can be defined as:

The number of multiples of the proportional response which are added to the control action per minute.

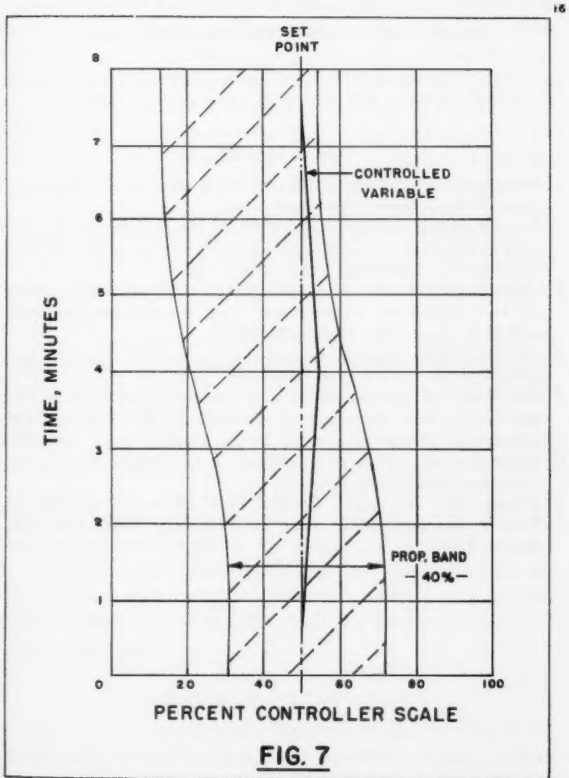


Figure 7. Effect of Reset on the Proportional Band.

Suppose, for example, that a given deviation from set point by the variable causes proportional action alone to change the valve position by 10% of its travel. If we then add one repeat-per-minute of reset action, the total valve movement in one minute for the same deviation would be 20% of full travel. This represents 10% due to proportional action plus 10% due to reset action.

This example also shows the relationship between the proportional band and reset action. The narrower the proportional band, the greater the valve movement for a given deviation. But the larger the valve movement due to proportional action, the greater the amount of action due to a given reset rate. We can see, then, that the narrower the proportional band setting, the greater will be the amount of corrective action due to a given reset rate. For this reason, stability in control action demands that reset be kept to a minimum with narrow proportional bands.

Rate Action

This type of control action is used only in conjunction with proportional action, never independently. It can be defined as:

A mode of control in which the position of the final control element is proportional to the *rate of change* of the controlled variable.

This is also commonly referred to as "derivative action," or "lead response."

Figure 8-A again shows the valve movement due to proportional action alone. Figure 8-B shows the movement of the valve which would be due to rate action alone. The algebraic sum of the two is proportional-plus-rate response, and is shown by Figure 8-C.

Rate action is commonly expressed in *minutes* of rate time. Rate time, in turn, is the time interval by which rate response *advances* the effect of proportional action alone upon the final control element. This is found by subtracting the time required for a given valve movement due to proportional plus rate response from the time required for the same valve

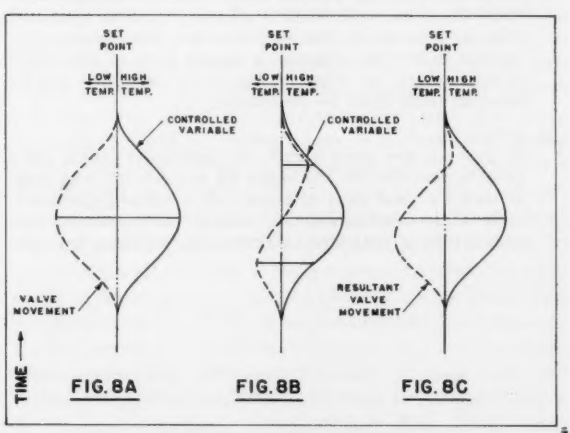


Figure 8-A. Proportional Action
Figure 8-B. Rate Action
Figure 8-C. Proportional Plus Rate.

movement due to proportional action alone. Suppose, for example, a deviation by the variable causes a valve to be moved to a 10% open position in 6 minutes, when proportional action alone is used. If, however, the addition of rate action causes the same movement to take place in only four minutes, we can say that our rate time is six minus four, or two minutes.

Rate action is used to "tune out" a cycling of the variable about control point. In general, it "gets the jump" on deviations from set point, and over-corrects in order to bring the variable back in the shortest possible time.

Proportional Plus Reset Plus Rate

Modern advanced automatic controllers generally offer a combination of the last three modes of control. The basic mode is proportional action, with adjustable settings for proportional band width, reset action, and rate action. Figures 5-A, 6-B and 8-B showed the effect on valve movement of proportional, reset, and rate actions alone. Figure 9 shows the ideal result when all three are acting in combination. This is the proportional-plus-reset-plus-rate mode of control which is used for tight control of modern industry's complex processes.

APPLICATION

Even after having mastered the theory behind the five major types of control action, the beginner is still stuck with the problem of which mode to use with a given process. Unfortunately, there is no simple answer to this. At best, there are two general rules which can be followed in selecting the controller for a given application.

1. *Know the Process*
   There is no substitute for making a detailed analysis of the process to be controlled. Such factors as the capacity, the range of the controlled variable, the various time lags in the system, and even the equipment available are factors in the selection. The most important decision to make, however, is just how closely control must be maintained. Is the process such that the variable can cycle about set point without affecting the final product? If so, by how much? The answer to this last question will usually determine whether a simple type of controller is satisfactory, or whether the more expensive multi-function units must be considered.
2. *Simplicity*
   In general, the more simple the controller which adequately does the job, the better off you are. It's very easy to spend a good deal of money on advanced electronic units while overlooking the value of the more common, simple type of controller. Maintenance, replacement cost, and initial price are all reasons for favoring simplicity when choosing the controller for a given process.

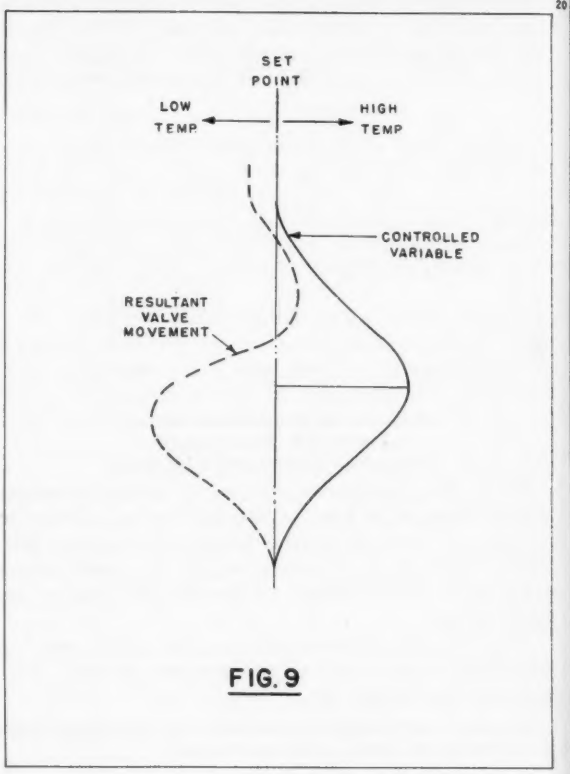


Figure 9. Proportional Plus Reset Plus Rate.

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"TRANSACTIONS I.E.& S. IN SCOTLAND"

RECENT DEVELOPMENTS IN LUBRICANTS FOR USE IN MARINE EQUIPMENT

ACKNOWLEDGEMENT

This article was presented before the Institution of Engineers and Shipbuilders in Scotland, on 24 January, 1956, and was published in Volume 99, Part 5, of the "Transactions" of that Society. The authors are V. W. David and L. J. Richards of Shell Research Ltd.

INTRODUCTION

It is now generally appreciated that modern lubricants must have a number of other properties in addition to that of being able to maintain a lubricating film between working surfaces. These include anti-wear properties in oils for use in internal combustion engines, anti-rusting properties in turbine oils and greases and good resistance to oxidation in almost all the top quality lubricants. In general lubrication *per se* is easy—if the selection of a lubricant depended solely on its ability to lubricate there would be little for the oil technologists to do. It is the other properties of the lubricant that frequently are difficult to achieve, and the progress that has been made in recent years in these directions forms the subject of the present paper.

From the many applications of lubricants in marine equipment the authors have selected a few examples designed to show how the oil technologist's increasing understanding of the factors determining performance of lubricants has been used to provide products which are much superior in many respects to those of but a few years ago. Improvements have not, of course, been restricted to the examples quoted, but cannot all be covered in the paper.

First, consider the prime movers, in particular the steam and gas turbines and the Diesel engine, and then specialty products such as greases and fire-resistant fluids.

STEAM TURBINE LUBRICANTS

In addition to its main function of lubricating bearings and reduction gears, a function which it must maintain over long periods of time, the lubricating oil in a steam turbine must serve as a coolant and must protect against rust the turbine parts with which it comes into contact. It must also frequently serve as a hydraulic fluid, for example, in governors and other control gear. A high quality turbine lubricant must therefore have anti-oxidant and anti-rusting properties as well as adequate load-carrying capacity, and these aspects of performance are briefly discussed.

The air and moisture which are inevitably present in the lubrication system, the operating temperatures which have risen with the development through the years of turbines increasingly compact in design and using steam at higher pressures and temperatures, and the constant contact of the oil with metals such as copper and iron, make heavy demands on the oxidation stability of the lubricant. Oxidation of the oil may lead to the formation of acids, sludge and, with the water present, permanent emulsions. Oxidation, therefore, leads to undesirable products, and high resistance to oxidation thus becomes an important requirement of the lubricant. This has, of course, been recognized for many years. A more recent study of the chemistry of these oxidation processes and the mechanism by which anti-oxidants are effective has shown the need for the careful selection of both base oil and additive to obtain optimum performance. In general paraffinic oils of high viscosity index are now used as base oils for the top quality range. Such oils are produced by complex solvent refining and dewaxing processes followed by sulphuric acid and/or earth treatments. The oxidation stability of such base oils is, however, still insufficient to meet the requirements of modern turbine installations. By using anti-oxidants of the correct type and at the correct concentration, products of outstanding resistance to oxi-

dation have been developed, which according to laboratory tests may give a life of up to ten times that of an uninhibited oil.

An increasing need has become apparent for turbine oils of higher load-carrying capacity than hitherto. This development has been stimulated by the Admiralty, which has been interested in the possibilities of savings in weight and bulk of gears on board ships. This can be accomplished by permitting higher specific gear loads, which can now be attained through the use of hardened and ground gear teeth and lubricants with sufficiently high load-carrying capacity. To impart such load-carrying capacity special compounds, so-called extreme pressure additives, have to be incorporated into the oil. It is too early to say whether these oils will find favor with merchant shipowners and whether in fact a need for such oils exists outside the Services.

It can therefore be seen that advances continue to be made in the quality of steam turbine lubricants which should go a long way towards providing industry with new products capable of meeting the ever-increasing technical requirements of modern steam turbine installations.

GAS TURBINE LUBRICANTS

The use of gas turbines has made spectacular progress in the aviation field but in the marine field they have only just got beyond the development stage. The well-known experiments of the Admiralty[1-4] and Shell Tankers Ltd.[5-8] may pave the way for a wider application of such engines in ships in years to come.

To the petroleum industry the lubrication of gas turbines for aviation applications has presented a number of novel problems. In particular, the required temperature range of operation (from ambient temperatures of, say, —50°F. or below to bearing temperatures at the hot end of the turbine of 550°F. or higher) is presenting special problems of thermal stability, resistance to oxidation, pour-point requirements and last, but not least, viscosity/temperature properties for the lubricant. This task has now been accomplished to a large extent through the use of specially synthesized lubricants which are really products of the chemical, including the petrochemical, industry.

For marine uses the conditions are, however, much less stringent; the low-temperature aspect is not important and the bearing temperatures are not yet as high as those in modern aviation gas turbines. There is therefore at present no need for synthetic lubricants for use in marine gas turbines: in fact the high-quality steam turbine lubricants already mentioned are proving adequate in the majority of marine and industrial installations to date. Some additional oxidation stability and load-carrying capacity may be needed for gas turbines in the development stage. From the experience already gained in the aviation field it can be stated with some confidence that the petroleum industry is in a strong position to meet the future requirements of industrial and marine gas turbines for some time to come.

INTERNAL COMBUSTION ENGINE LUBRICANTS

Much has been written of internal combustion engine oils containing additives, or "heavy duty (HD) oils" as these are commonly termed. In general these oils, compared with non-additive mineral oils, give greatly improved performance in high-speed splash-lubricated engines as regards ability to reduce engine wear and maintain pistons and piston-ring grooves, and indeed all the internal parts of the engine, substantially free from deposits which, if allowed to form unchecked, would lead to malfunctioning. In terms of the number of engines, the high-speed automotive Diesel undoubtedly presents the largest field of application of these HD oils, although they are very successfully used in many marine units, particularly in the type of engine used for auxiliaries and for the propulsion of smaller vessels. Since the potentialities of the HD oils have been adequately covered in numerous publications in recent years, a general familiarity with this type of oil will be assumed.

It is intended, however, to describe briefly the development of a novel lubricant which has been very successful in reducing wear of large low-speed marine propulsion Diesel engines, particularly those burning bunker oil, and it may be of interest to trace how in fact the development of this type of oil was linked with the now more conventional HD lubricant.

Extensive research over many years revealed that much of the wear of engine cylinders and piston rings could be accounted for by direct chemical corrosion.[9] In the combustion of fuel above the piston, strong organic and inorganic acids are produced and a proportion of these condenses on and reacts with the cylinder wall. The products of these reactions are continuously removed by the rubbing action of the piston rings on the cylinder surfaces, exposing new metal to the chemical attack. Thus a process of "corrosive wear" is brought about which varies in its severity according to the conditions under which the engine is run. Low cylinder temperatures are conducive to acid condensation and aggravate the problem, as does a high fuel sulphur content,[10] which leads to a more copious production of strong acid.

Successful attacks on the problem of corrosive wear have been made in the oil industry, for it was discovered that alkaline materials could be added to the lubricant which could neutralize corrosive acids formed in the combustion process before they reached and damaged the cylinder surfaces. Accordingly alkaline materials which were oil soluble and satisfactorily thermally stable were developed and used as anti-wear additives in HD lubricants for high- and medium-speed Diesel engines, with the outstanding results with which everyone is familiar.

It will be clear from the broad principles outlined above that in order to be successful in reducing wear there must be a chemical balance between the quantities of strong acid reaching the vulnerable cylinder

walls and piston rings and the quantity of alkaline anti-wear additives supplied to that region by way of the lubricating oil. With most types of fuel normally used in high-speed Diesel engines the provision of this balance has presented but little difficulty, for the acid-forming propensity of this type of fuel could normally be readily matched with the aid of the oil-soluble additives of the type used in some of the more conventional HD lubricants. With bunker fuels, however, such was not the case because of the large quantities of corrosive acid formed during the combustion of such fuels. Thus although conventional straight mineral oils met the actual lubrication requirements of engines using these very heay fuels, the technical advances (in terms of reduced wear and engine fouling) which had been made in lubricants for high- and medium-speed engines had not been available to the large marine engine. In principle the problem with these heavy fuels was the same as with lighter fuels, that is, the high rates of corrosive wear obtaining could be effectively reduced by using sufficient quantities of anti-wear additives of the type now used in HD oils, but the necessary quantities of these expensive materials were prohibitive.

A novel and practical solution satisfying both technical and economic considerations has been found in a lubricant which carries the required quantities of anti-wear additive dissolved in the water phase of a stable water/oil emulsion. A considerable saving in manufacturing cost is achieved by thus eliminating the requirement that the anti-wear additive be oil soluble, without sacrifice of the lubricating properties in the hydro-dynamic sense, for this latter requirement is met by the oil phase of the emulsion. Although developed with the primary objective of reducing wear, it was known that the new lubricant would reduce fouling of pistons and cylinders for, where acids formed in the combustion process go unchecked, in addition to causing wear they aggravate deposit formation. Thus a further benefit obtained from the type of lubricant described is a considerable reduction in deposition on pistons and in the ports of two-stroke engines. The performance of this novel lubricant in extensive marine engine application provides ample confirmation of the soundness of its technical foundation and it is not intended to list any detailed results of trials at sea. Some of these have already been given elsewhere[11-13] and it is perhaps sufficient to mention that reductions in cylinder liner wear of the order of 70 per cent have been obtained. The present purpose, as stated in the introduction, is to depict the growth of basic knowledge in certain fields rather than to chronicle the performance of given products.

LUBRICATING GREASES

In ships lubricating greases are mostly used in ancillary equipment such as electric motors and generators, fans, winches, etc. A recent development in the grease field is the so-called "multi-purpose greases." As their name implies these products cover a wider variety of requirements than earlier greases, combining a wide range of operating temperature with resistance to water. Although multi-purpose greases are somewhat more expensive than conventional greases, the increased cost is usually compensated by a reduction in stores inventory, by increased operating life and by avoiding the possible use of unsuitable lubricants in critical applications.

Fretting corrosion is a type of surface damage occurring between closely-fitting machine components, such as splined shafts and universal joints, when subjected to vibrations or reciprocal oscillations. It produces irregular corroded and pitted areas and, when one of the contacting surfaces is a ferrous metal, is always accompanied by oxide detritus, a cocoa-like residue. This reddish debris has been identified as a ferric oxide (Fe_2O_3), a product not usually associated with corrosion as ordinarily understood, which acts as an abrasive at the interfaces. Damage due to fretting may be minimized by eliminating vibration or preventing mutual slipping, as by bonding the surfaces by means of a plastic material, or by the use of lubricants. A very limited number of greases has been found to provide adequate protection against this type of wear.

FIRE-RESISTANT FLUIDS

Any system which involves a large quantity of petroleum products can, of course, present a potential fire hazard. Fluids with varying degree of non-inflammability have from time to time been put forward. The earlier products had some disadvantages such as toxicity, lack of lubricating properties, attack on seals, corrosivity, etc., with the result that they were not used very widely. In recent years the main interest in this field has been in the development of non-inflammable hydraulic fluids for aircraft, and only more lately for industrial purposes. The types of products which are now under development are based on either water or synthetic lubricants and no doubt the shipping industry will hear more about such fluids once success has been achieved.

DESIGN OF LUBRICANTS

It is evident from what has been said that modern high-quality lubricants are complex compositions consisting of base mineral oils to which have been added additives with specialized functions such as detergency, corrosion inhibition, load-carrying capacity and so on. It might be thought that in designing a lubricant for a specific application all that was necessary was to select a base oil of appropriate viscosity and to add to it various additives from bottles off the shelf which impart to the oil the desired special properties. This, however, is not the case. The design of a lubricant is often most complex and the final product is frequently a delicate balance of conflicting requirements which has been arrived at as a result of a thorough understanding of the problem in question. This can perhaps best be illustrated by considering some of the problems confronting the petroleum technologist in the design of modern steam turbine lubri-

cants, to which reference has been made earlier in the paper.

The requirements which all potential additives must satisfy for use in steam turbine lubricants include such obvious factors as adequate solubility in the mineral oil over the temperature range of operation, chemical stability especially in the presence of water, since many chemicals are gradually decomposed (hydrolyzed) by water, and non-volatility (relative to the base oil) to prevent preferential loss of additive by evaporation. For lubricants containing more than one additive, compatibility of the additives is another overriding requirement.

Oxidation or aging of the oil leads to increased viscosity and acid formation which, if it develops too far, can lead to corrosion of metals and to the formation of stable emulsions with the water present in the oil. Oxidation inhibitors delay the formation of these acids to a greater or lesser degree depending on the efficiency of the inhibitor, which in turn is in part determined by the nature of the base oil and the degree of refining it has received. Among the most powerful inhibitors are certain types of sulphur compounds which are, however, excluded from use in steam turbine oils because they are too corrosive to copper at operating temperatures.

Though rusting has always been a problem, it is known that the oil oxidation acids in used oils do help to reduce rusting. The use of oxidation inhibitors in oils can thus be expected to decrease the anti-rusting properties of an oil slightly. Anti-rust agents are added to protect against rusting but their selection is most tricky, since most compounds with anti-rust properties are of a type which encourages the formation of emulsions and some are known to have an adverse effect on the oxidation stability of the oil.

Load-carrying capacity (extreme pressure) additives are chemically reactive compounds, for they depend for their action on the instantaneous reaction with the metal surface at the high temperature occurring in the region of gear teeth contacts. They must, however, not be so reactive that they attack all the metal parts with which the bulk oil comes into contact, for this would not only lead to excessive corrosion but also to rapid additive depletion resulting in loss of performance. The chemical nature of extreme pressure agents is such that the majority of them affect the demulsifying properties of the lubricant adversely. These considerations limit very considerably the choice of suitable extreme pressure additives.

CONCLUSION

It is hoped that this necessarily brief paper shows the results of careful study in the research laboratories of the petroleum companies into several aspects of marine lubrication. Some progress has been made in recent years leading to the development of new and sometimes unconventional products as well as improvements in existing grades. It can perhaps be claimed that no serious difficulties are at present outstanding in the field of marine applications.

The Authors hope that the paper has also been able to show that the design of a high-quality lubricant is the task of lubrication specialists. Their efforts must, of course, be backed by the highest standard of quality in the manufacture of the oils as well as the additives. It will be realized that the indiscriminate mixing of oils from different sources or the blending of base oils with purchased additives by the customer is not likely to result in products capable of giving optimum performance.

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B. H. TYTELL and H. S. PREISER

CATHODIC PROTECTION OF AN ACTIVE SHIP USING ZINC ANODES

THE AUTHORS

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Boris H. Tytell is a research chemist in charge of the Research, Development and Consulting Section of the Chemical Laboratory at the Boston Naval Shipyard. He has been intimately concerned with marine corrosion problems since he entered Government service in 1930. He received his B.S. degree in Chemistry in 1921 from Brooklyn Polytechnical Institute and spent two additional years pursuing graduate studies there. He is an active member of the Electrochemical Society, National Association of Corrosion Engineers and The Society of Plastics Engineers.

ABSTRACT

Low iron, special high grade, zinc anodes were installed on the bottom of the YTB-542 for a study of their performance as sacrificial anodes. Hull-potential readings were taken weekly for a fifteen month period, after which the vessel dry docked and the hull examined. Protective potentials, referred to silver-silver chloride half-cell, of –0.85 to –0.90 volt were maintained with the ship at rest and averaged –0.78 volt, when underway. The condition of the hull was excellent.

HISTORY

ZINC AS A GALVANIC ANODE has been used for over a century. The British Navy used zinc anodes in 1824 to prevent corrosion of copper sheathing on wooden ships. (1) With the advent of steel hulls fitted with bronze propellers, a galvanic cell was established which caused excessive corrosion of the steel in sea water, particularly in the stern area. Zinc anodes, coupled to the steel in the stern area, suppressed this corrosion in part. However, after short periods in service, dense corrosion products accumulated on the surface of the zinc anodes and restricted the flow of current such that protective potentials could not be maintained. Thousands of zinc anodes, removed from ships over the years, according to Navy Department Records, were found to have about 65 per cent of their original weight while the stern areas were found to be badly corroded.

IMPURITIES IN ZINC

The common trace impurities generally found in zinc of various commercial grades are: lead, cadmium, copper, and iron. Many investigators noticed that zincs containing large amounts of these trace impurities behaved differently than the purer grades of zincs. (2) Extensive research on the effects of these impurities on anode performance disclosed that traces of iron in excess of 0.0014 per cent were mainly responsible for the erratic behavior of special high grade zinc. (3) (4) A direct result of these investigations was the issuance of a new military specification

on zinc anodes for cathodic protection applications. The improved anodic behavior was attributed to the altered character of corrosion products which naturally form on the zinc.

MOUNTING OF ZINC ANODES

New methods of mounting were devised to insure foolproof mechanical and electrical attachment of the zinc to the structure. The previous arrangement of drilling the zincs and bolting them to studs which were welded in the hull was discarded in favor of welding an anode to the hull by means of protruding cast-in galvanized straps.

It was found by experience that open spacing of anodes in lieu of close grouping increases their current output and improves their current distribution.

SERVICE TEST CONDUCTED

In view of the laboratory data available on the anodic behavior of high purity zinc with an iron content of less than 0.0014 per cent a series of service tests were initiated for the purpose of establishing the validity of this new information. Zinc, as a galvanic anode, is most practical in installations where adequate current requirements for cathodic protection can be met by relatively low driving potentials. With this factor in mind, a well painted harbor craft, operating in high conductivity seawater, was chosen for this experiment. The total bottom area of the ship is about 2,500 square feet and the area of the manganese-bronze propeller is approximately 50 square feet.

CATHODIC PROTECTION INSTALLATION

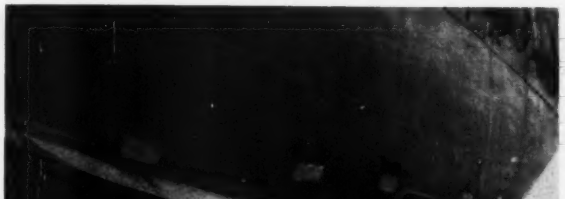
In July 1954, thirty cast-in strap, zinc anodes (Specification MIL-A-18001, type ZHS) were welded to the bottom of the YTB-542, fifteen anodes on each side. Figure 1 is a close-up of a typical anode. The zincs were spaced uniformly from frame number 5 to the after perpendicular as shown in Figures 2 to 4.

Official United States Navy Photograph

Figure 1.—Type ZHS zinc anode mounted on hull.

Official United States Navy Photograph

Figure 2.—Arrangement of zinc anodes on hull—port side, forward.

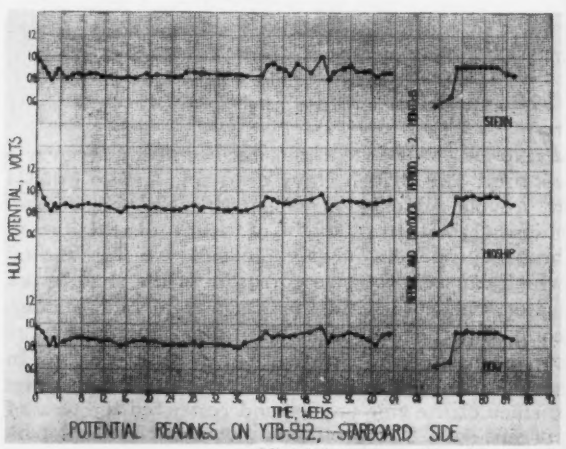


Official United States Navy Photograph

Figure 3.—Arrangement of zinc anodes on hull—port side, midships.

Official United States Navy Photograph

Figure 4.—Arrangement of zinc anodes on hull—port side, aft.



Official United States Navy Photograph

Figure 5.—Graph of hull potential (Ag-AgCL) versus time. Readings taken with ship at rest.

The hull had been painted in April 1954 with the standard Navy hot plastic system (Navy formulas F-117, F-14N, and F-15HPN) and was in good condition at the time of installation. See Figures 2 to 4.

POTENTIAL READINGS

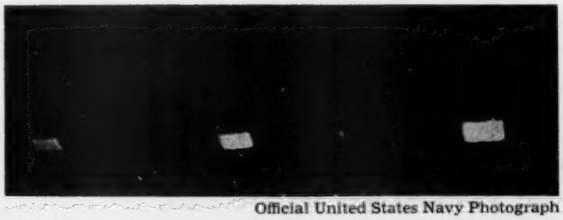
Hull potential readings, using a silver-silver chloride reference electrode and a potentiometer-voltmeter, were first obtained by Boston Naval Shipyard personnel on 21 July 1956, with the tug at rest. Potential readings, with the tug at rest, were taken at weekly intervals at 6 and 12 foot depths from 21 July 1954 to 21 October 1955, except during the period that the tug was under repair. Whenever posssible, potential readings were also obtained while the tug was underway at a speed of 7 to 10 knots, using a trailing silver-silver chloride reference electrode. A plot of potentials of the ship at rest is shown in Figure 5. The potentials of the ship when underway dropped slightly, averaging about –0.78 volt. The water around Boston Harbor is normally saline having a resistivity in the order of 40 ohm-centimeters.

OBSERVATIONS ON DRY DOCKING

Examination of the underwater hull immediately after dry docking the tug on 1 November 1955 disclosed the following:

Official United States Navy Photograph

Figure 6.—Appearance of zinc anodes and hull after 15 months' service—port side, forward.



Official United States Navy Photograph

Figure 7.—Appearance of zinc anodes and hull after 15 months' service—port side, aft.

Official United States Navy Photograph

Figure 8.—Appearance of zinc anodes and hull after 15 months' service—stern view.

(1) The paint film on the tug's bottom was in excellent condition.
(2) Only about 20 per cent of the zinc had been consumed during the 15 months of the tug's operation.
(3) Negligible amounts of zinc corrosion products were observed on the surfaces of the zinc anodes.
(4) No corrosion was observed on the tug's bottom, rudder or propeller.
(5) One zinc anode showed no deterioration whatsoever.
(6) A typical zinc anode, removed from the tug's bottom, weighed 18.5 pounds. (A loss of 4.5 pounds from the initial 23 pounds.)

The condition of the zinc and the hull is shown in Figures 6 to 8.

DISCUSSION

As stated before, zinc anodes of low purity did not protect the stern area of vessels adequately, and that 65 per cent of a zinc anode was not available because of corrosion-product incrustation. This is in marked contrast with the results of this investigation where complete cathodic protection had been obtained. The appearance of the zincs signifies that they will continue to be effective as long as they last. To protect 2,500 square feet of well painted hull and 50 square feet of bare manganese bronze propeller, only 135 pounds of zinc was consumed from the 690 pounds available. The average current density calculated from this weight loss to protect the hull, allowing 25 milliamperes per square foot for the propeller, is 1.1 milliamperes per square foot. In view of the high percentage of zinc left on the anodes, and the excellent condition of the tug's bottom, the YTB-542 was returned to service with the same zinc anodes and without repainting the hull. Figure 9 shows the fine appearance of the main sea chest, usually a troublesome corrosion area, after 15 months of exposure under cathodic protection conditions. Potential readings will be taken until the zinc anodes are completely consumed.

Official United States Navy Photograph

Figure 9.—Appearance of main seachest after 15 months' service showing complete absence of corrosion and paint deterioration.

The even consumption of the zinc anodes and the good appearance of the hull indicate that effective distribution of current was obtained.

No explanation can be given for the lack of corrosion products or weight loss observed on one zinc. A chemical analysis of the zinc showed it to conform to

Official United States Navy Photograph

Figure 10.—Appearance of a zinc anode after 15 months' service which has corroded on both top and bottom surfaces. Note the excellent condition of the paint adjacent to the anode.

the composition requirements of Military Specification MIL-A-18001.

Another point worthy of note is that the zincs were installed without the usual practice of embedding the faying surfaces in zinc oxide paste. Apparently this oversight did little harm except that anodic action did take place on some zinc anode faying surfaces. Figure 10 shows an anode corroding on both the top and bottom surfaces. No paint damage in way of the anode was observed.

CONCLUSIONS

High-purity zinc, conforming to Military Specification MIL-A-18001, provided excellent cathodic protection to an active ship in service.

Protective potentials both underway and at rest were obtained continually during the 15 months of the investigation.

The condition of the tug's bottom was excellent. No adverse effect from the zinc cathodic-protection system was found on the Navy hot-plastic paint.

Distribution of current from the spaced anodes was effective.

Based on the low rate of zinc consumption during the first 15 months' period, it is anticipated that this combination of paint and cathodic protection will last 4 or 5 years. Hot plastic systems have demonstrated antifouling life well within this range on Reserve Fleet vessels.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of Bureau of Ships' personnel and Boston Naval Shipyard personnel in performing this experiment.

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The Bureau of Ships expects to eventually equip all guided missile ships with fin stabilizers. The British Denny-Brown stabilizers have been installed in the destroyer "GYATT," and another type, developed by Sperry, will be installed on "COMPASS ISLAND" (EAG153). The latter ship will carry the JUPITER guided missile.

"MECHANICAL ENGINEERING"

THE SHORTAGE RE-EXAMINED

ACKNOWLEDGEMENT

James R. Killian, Jr., President, Massachusetts Institute of Technology, made this address at a meeting of the American Society for the Advancement of Science, in Atlanta, Georgia, on 27 December, 1955. Reprinted from the May, 1956, edition of "Mechanical Engineering."

THERE IS A STORY ABOUT a cello player who sawed continuously on a single note. His wife remarked to him that other cello players seemed to move their fingers up and down the strings, producing less monotonous sounds.

"Oh!" replied the cellist, "they are looking for the note. I've found it!"

Recently I have been asking myself whether, along with many others, I have *the* note or whether I have not restricted myself to too few notes in discussing our current manpower requirements in science and engineering. I have an uneasy feeling that we may have become bemused by numbers and oversimplified quantitative measures and remedies in evaluating our manpower needs in the broad field of technology— defining technology as the combination of science, engineering, and production. That we have an acute shortage of available effectively used competence in many fields of technology there can be no reasonable doubt. Neither can there be a reasonable doubt any longer that this scarcity is a clear and present danger to the nation and to the entire free world.

My theme does not involve challenging this scarcity or its danger to the nation. It does emphasize the need for a better understanding of the nature of the shortage and of the paramount importance of qualitative factors in any plan for meeting our manpower needs. I wish particularly to examine ways in which our educational system must respond to our manpower needs and how current attitudes and values with respect to science may affect the supply of scientists.

If we are to promote action on a grand scale for augmenting our scientific resources, we need to look at every factor that might help. Consequently I wish to suggest some of the elements of a grand strategy which must be stressed *along with* increasing the quality of our science teaching and countering Russia's remarkable technological build-up and the grim threat it holds for us.

SHORTAGE OF TALENT

With these guide lines before us, let us now look at the nature of the present dearth of scientists and engineers in the face of a greatly increased demand. It is not simply a shortage of men. First and basically, it is a shortage of intellectual talent adequately educated and in the right place. Second, it is more a shortage of specific talents and skills adaptable to specific areas than a general shortage of numbers.

The shortage of high talent is aggravated by the fact that too many young people of exceptional intellectual ability drop out of our educational system before they have achieved an education which fully exploits their abilities. The loss between high-school and college graduation has been repeatedly reported. Of the ablest 50 per cent of high-school graduates only about a third show up on the list of college-degree recipients. Of the top 2 per cent of our high school graduates only about two thirds now graduate from college. From these facts we draw two morals. The first is that too many of our ablest youth fail to get the kind of education their abilities deserve. The second is that without dropping standards we can achieve only a limited increase in our college population by stepping up the percentage of high-school graduates who go to college. Both these conclusions stress the importance of motivating and using more of our exceptional talent and directing our attention to its conservation and cultivation.

In a recent letter prepared for the subcommittee on school goals of the Committee for the White House Conference on Education, Mr. Dael Wolfle has made the following observations about the relation of the scientist shortage to our resources of talent:

"We must plan our educational programs to encourage more of the bright youngsters to prepare for scientific and technical careers. It is debatable, however, as to whether the most effective method of securing that end is to concentrate on young people

who may become scientists or to concentrate on those of high ability. A scholarship for a student to study science may help, but not if his high-school experience has been so discouraging as to turn him away from higher education in any form. Improved high-school instruction in science may help, but not if the youngster grew up in an environment that puts high value on getting out of school as soon as possible.

"The loss (between high school and college) could be reduced by provision of a larger number of college scholarships. It could be still further reduced by so changing the high-school curriculum as to provide a more stimulating and challenging four years of learning and experience for the brightest high-school students. It could be still further reduced by those, necessarily slow, social and cultural changes that would place greater emphasis upon the importance of education, as distinct from diplomas, and upon the importance of recognizing high ability and giving it full opportunity for development wherever it may be found.

"Since the effectiveness of different methods is debatable, but the importance of scientific manpower perfectly obvious, my own preference would be to devote our educational, scholarship, guidance, and encouragement efforts to boys and girls of high ability, whatever their fields of special interest, to plan educational programs for as much flexibility as possible by keeping alternative paths open, to keep careful watch over the number of students preparing for careers in science, and only to abandon the broader and, I believe, more socially desirable approach in favor of special treatment for prospective scientists if it appears that we are not likely to get enough scientists out of our broader attack upon the general problem of recognizing, encouraging, and developing high ability."

Augmenting the Talent Pool

I find myself in agreement with Mr. Wolfle's analysis and his preferred policy. For the long pull I think the nation would be better served by augmenting the total pool of exceptional talent so that all of our professions benefit rather than by giving exclusive attention to getting more talent into science and engineering, even though the need for manpower in these fields is at the present time the most urgent. If we attempt to build up science and engineering through methods which apparently deprive other professions of a fair share of the talent pie, we may generate a host of undesirable reactions and side effects inimical to the welfare of science in the long run. We might also attract into science too many whose talents and predilections were more compatible with other kinds of careers and who would therefore become indifferent scientists and engineers .

Lack of Understanding in Secondary Schools

One of the reasons we are in trouble now is that some secondary teachers and administrators have placed a low value on science and have shown an inadequate understanding of its intellectual requirements and its importance to our society. As we seek to give science its proper place and emphasis in the secondary school, I hope that we do not overshoot and place a low value on other fields and thus bring about their neglect.

Whether there is agreement among scientists with the line of action proffered by Wolfle, I think there will be agreement that any grand strategy for augmenting our scientific manpower must be related to a concerted effort to identify, encourage, and more fully educate the top talent among our youth.

QUALITATIVE ASPECTS OF MANPOWER SHORTAGE

In reviewing the clinical evidence on the nature of the manpower shortage, let us next take a reading on the qualitative aspects of the current excess of demand over supply, using as our example the field of engineering. One has only to talk with the placement officers of our scientific and technological institutions to get revealing evidence of the increasingly selective demand for engineers. Employers are not looking merely for "bodies" with degrees; they are looking with a critical eye for very special qualifications—for a sound education in fundamentals, for analytical power, for a grasp of the new and advanced fields of technology. They are looking less for specialized competence at the baccalaureate level and more and more for men who have the versatility to follow successfully any one of several specialties. They are looking more and more for men and women with graduate degrees.

Advancing Technologies

These special placement demands indicate a great shortage of young engineers with a mastery of engineering science and thus a competence to handle new, advancing technologies, such as data processing, internal aerodynamics, energy conversion, communications, servomechanisms, "molecular engineering," and solid-state physics for the design of materials, and similar functional components of technology.

Thus industry and government are pressing the colleges for engineers of more advanced education and analytical powers. They are looking for men with a fundamental integrated education in science, engineering, and the humanities rather than for men specialized in some field of technology at the expense of fundamentals. Employers want more scientists and engineers, but they don't think they are meeting their needs by employing narrowly educated ones. In this new pattern of demand lies the pattern for a modernized engineering education as I intend later to emphasize.

Need for Exceptional Qualifications

Similarly, in the basic sciences our most pressing needs are for those scientists who have the imagination and trained creative power to make the discoveries and generate the new concepts which advance science. Quite properly we hear much about the need for basic research and the funds to support

it. These needs indeed are great, but greater still is the need for more scientists who have trained talent, the motivation, and the conceptualizing power to make basic research really basic.

In stressing the need for exceptional talent, I do not minimize the critical shortage of the rank and file of good competent scientists and engineers. Flag officers are not enough to provide a strong scientific attack force, but the really acute shortage is now in the flag-officer group.

These qualitative characteristics of the present shortage clearly affect the design of any comprehensive strategy for relieving the present dearth.

AT THE SECONDARY-SCHOOL LEVEL

In the secondary schools the first order of business is to shore up the sagging emphasis on science and to begin filling in the decimated ranks of science and to do this, not with culls from other fields, but with teachers possessing a grasp of science and the perception to identify and stimulate youngsters with the bent and capacity for science. The dean of one of our schools of education recently came to me with the evidence that the secondary-school system was recruiting negligible numbers of top science majors from the colleges, especially our institutes of technology. In competition with other fields, it could not offer them a sufficient attractive career. He also noted the apparent reluctance of our science departments and schools to encourage bright young graduates to go into secondary-school science teaching, a situation that was also noted in the first report of the Science Teaching Improvement Program of which the American Association for the Advancement of Science is one of the sponsors. He expressed pessimism about sustained improvement in science teaching unless we could induce more really first-rate young scientist bachelors to elect secondary-school teaching as a career. It is fine to upgrade existing science teachers and to supplement them with part-time personnel, but these are only partial solutions.

The Vocational Counselor

The influence of the secondary-school vocational counselor is growing steadily, and it is of obvious importance that these counselors understand the scientific manpower needs of the country. It is particularly important that these counselors not harbor misapprehensions about scientific and engineering careers, particularly because so many of them have had no opportunity to gain any insight into science. There is the need which Mr. Wolfle has stressed for earlier identification of scientific talent, such identification coming as early as the seventh grade. There is the need for more rigor, more emphasis on excellence in the secondary school. As President DuBridge has said, we need "to make thinking popular." I suspect that much of the flight from science at the secondary-school level has resulted from the fear of science as a difficult subject to study. In the pejorative argot of the high-school youngster, only a "brain goes for science" and sometimes a brain is considered a "queer". With such attitudes in the ascendancy, science is avoided in favor of subjects which are less demanding, more descriptive, more easily passed, more easily taught.

Parental Duty

Blame for this aversion to rigorous thinking rests with parents even more than it does with the schools. So far we have managed to get along in the United States by displaying an attitude of condescension toward hard intellectual labor in our schools. There has been avoidance, if not evasion, of the intellectual tax which must be paid if our intellectual budget is to be balanced. Any strategy for strengthening manpower resources must give attention to this fatty degeneration (if I may change the metaphor!) in our education. At a time when we are forced to match wits on every front with an alert enemy of growing prowess, America's survival requires that the American attach a higher value to the hard labor of rigorous thought. Certainly progress in science and technology requires this kind of intellectual work—work which can be invigorating and absorbing even though hard and demanding.

Flexibility of High-School Program

Other aspects of high-school education require attention as we seek to augment our manpower resources. The high-school program should be flexible, so that an early election of program does not commit a boy or girl irrevocably to some prematurely selected career or educational program. Too often gifted young people without all the facts before them elect a program which makes it difficult for them to go to college, if later their sights are raised or their circumstances change. The vocational high school is vitally important in our educational scheme and serves many young people admirably but it never should be so managed or organized that youngsters of college caliber who elect the vocational program find themselves too late unprepared in motivation or training for college. This need for flexibility has a direct bearing on the conservation of exceptional talent for higher education. We must avoid creating dead-end kids who become caught in educational cul de sacs when they have the ability to travel farther up the avenue of education.

What the High Schools Must Accomplish

In making these observations about secondary-school education, I must make clear my conviction that public schools have a much more comprehensive job to do than preparing young people for college. I am surprised at the number of college people, particular college professors teaching freshmen, who think that the exclusive mission of the high school is to prepare youngsters for college—preferably *their* college. I am equally surprised by others who apparently ignore the fact that one of the extremely important functions of schools *is* to prepare youngsters

for college. Because of my natural interest in the education of scientists and engineers, I find that I must keep reminding myself that, although the education of our future scientists and engineers has been neglected with effects endangering the nation, the education of other kinds of people is also important. We should not neglect any one group of youngsters in order to strengthen another.

Secondary schools, it must also be remembered, play a major part in maintaining our fluid classless society. Criticism of the high schools for not confining their programs to teaching the intellectual skills is neither fair nor in the interest of the nation. I hope that methods for strengthening science teaching and increasing the numbers of scientists will not result in unfortunate distortion of this broader function of the public-school program.

Designed to Help All Children

Our schools should be designed to help all children, and the needs of children of different abilities, different backgrounds, and different aspirations. But we do need to come to a better understanding of the importance of priorities and the necessity of discriminating choices so that we can temper our prodigality of aims by sobering considerations of quality, social and intellectual needs, and achievable goals.

At this point in the evolution of our schools the highest priority should be given to better provision for our intellectually gifted young people, greater stress on the more rigorous teaching of intellectual skills, and on higher standards of excellence for both teachers and pupils.

Improvements in Science Training

I feel that success in promoting these broader objectives for the schools will carry with it improvements in the motivation and teaching of future scientists. I am very skeptical of such expedients as accelerated programs for those interested in science or any efforts to make a sharp vocational distinction between those interested in science and those who are not. It does seem desirable to provide programs in which the intellectually gifted youngster, regardless of his ultimate specialization, can go farther and deeper. Experimental programs are showing that such programs can make it practical to give advanced standing in college and thus to cover more ground during the college period.

AT THE COLLEGE LEVEL

At the college level there are many improvements available to us for strengthening our scientific and engineering education. The liberal-arts colleges are of course the principal sources of candidates for our graduate schools of science. The Wesleyan study and others have shown how remarkable has been the success of a number of small liberal-arts colleges in preparing men and women to become distinguished specialists in science. This stresses the importance of still further strengthening the teaching of science in this type of institution and thus attracting more college students to major in science and proceed on to graduate school. Increasing the number of science majors in the liberal-arts college is one of the quickest ways available to us to increase the number of scientists. It will require an attitude in these institutions that does not underrate science—an attitude, as I shall emphasize later, that sees an understanding of science as one of the requirements of effective liberal living in our technological society.

Shortage of Science Teachers

As the presidents of liberal-arts colleges well know, there is also a shortage of *college* teachers of science, both in terms of numbers and quality. As we alert the nation to the need for more teachers of science in the secondary schools, we also should stress the equally serious needs of our colleges, particularly those institutions where little research is done, as industry and other agencies have drawn the promising young material away by providing opportunities to do research and development and by higher compensation.

I advocate more grants and fellowships to enable professors of science in liberal-arts colleges to have time off from teaching to do research or to have firsthand contacts with creative work in science in our universities or in industrial or government laboratories. More thought has been given to making such opportunities available to high-school science teachers than to science teachers in the small liberal-arts colleges. Wherever he may be, the satisfaction, the professional growth, and the teaching effectiveness of the science teacher are enhanced if he can do research or investigation or maintain periodic contact with these activities.

It is not only the liberal-arts colleges that have a problem in providing the environment and professional opportunities adequate to attract and hold able scientists as teachers. Our professional schools of science and engineering have suffered in the competition for top-flight men. Again using the engineering schools as an example, let me review their problems as they seek to respond to the growing demand for engineeers, particularly the more selective demands which I have already described.

Competition From Industry

Against the higher compensation and other attractions offered by industry and other noneducational organizations, engineering schools are now more vulnerable and more in danger of serious deterioration than other educational institutions using scientists. They are more vulnerable, even, than the schools and departments of science. The university and the institute of technology are natural habitats for creative scientists. They are not, generally speaking, quite so natural habitats for engineers, whose professional work lies so much in industry and in the field.

The engineering schools are especially vulnerable now because their young and imaginative graduates and teachers—especially those in the advancing,

growing fields of technology—are more in demand for noneducational employment than any other group in our educational institutions.

If engineering education is to meet this challenge and reverse or even retard the spreading scarcity of quality in engineering schools that has weakened science teaching in high schools and other kinds of institutions, it must find a way to make engineering schools a more attractive environment for top-flight engineers and thus for top-flight teaching of future engineers.

The Teaching Load

Even though their enrollments have been down, the teaching loads in our engineering schools—exceptions exist, of course—are very high, with the result that their faculties have too little opportunity for the creative work that leads to further professional development both as teachers and engineers. An informed observer recently estimated that only 10 to 20 per cent of our engineering schools had average teaching loads as low as twelve hours per week or less. When we reflect upon the fact that these institutions are hard pressed to maintain their present level of staffing, we can readily surmise how difficult it will be greatly to increase enrollments and to enlarge graduate study without further burdening faculties and without a reduction in the quality of education.

Stronger Graduate Programs

The success of engineering education in attracting and holding more first-rate teachers will depend upon accelerating the development of more and stronger graduate programs. The graduate school and the research associated with it can provide engineer-teachers with the opportunities for professional activities and growth as engineers which they now find chiefly in practice outside of educational institutions. In those engineering institutions where strong graduate schools exist and where there is a fruitful alliance with basic science, an environment satisfying to first-rate engineers has been better achieved.

Engineers With Advanced Training

Of course, more graduate study in engineering is essential for another reason. We need more engineers with more advanced training to meet the increasingly complex technological needs of our society. The engineering profession or our society can no longer be adequately served by a professional engineering education that is predominantly undergraduate. While this undergraduate education has great strength and a vital role in our total national educational task by providing a form of general education built around professional objectives, it must be extended by more advanced training both in educational institutions and in industry. We must also attract into the undergraduate schools more of the students who have the intellectual qualifications for graduate work.

While qualified bachelor's degree recipients in engineering frequently go on for graduate study in other fields such as the physical sciences and management, the amount of advanced study in engineering still seems small compared to the advanced study *required* by the professions of law and medicine. The degrees are, of course, not comparable, but it is nevertheless of some significance that the number of advanced degrees in engineering, both master's and doctor's, in 1953-54 totaled about 4800 (of this total, only 594 were doctorates) as reported by the U. S. Office of Education, while the total of M.D.'s and LL.B.'s totaled 6757 and 9898, respectively. Without dwelling on the impropriety of comparing apples and doughnuts, the implication is clear that the engineering profession suffers in comparison with the other great professions in the amount of advanced study undertaken. If engineering is to meet the challenge of our advancing technology, it must promote more graduate study of top quality.

A New Approach to Engineering Education

Many educators are also advocating changes in undergraduate engineering courses, and after a long period of *status quo-itis*, engineering education seems to show signs of the bold experimentation and innovation that marked it in its early days in the United States when it was struggling to throw off the unsympathetic sanctions of classical education. There is a spreading conviction that the engineering curriculum must include a larger content of basic science, less of its traditional compartmentalization, more emphasis on such fundamental functional aspects of engineering as materials ,thermodynamics, fluid flow, and energy conversion. These concepts lead inevitably to a more fundamental curriculum for all fields of engineering, with specialization deferred to the last two years of the undergraduate program and even reduced in these two years in favor of pushing real specialization into the graduate years or into the in-service training programs given by industry itself.

Notable new programs representing some of these points of view are now being tried at a number of institutions. Industry, acutely aware of its needs for engineers of more depth, power and versatility, is encouraging these efforts. Together these new goals seem to presage an increasing number of institutions dedicated to programs that are less vocational and specialized at the undergraduate level and fundamental enough in their basic science and advanced enough in their mathematics and humanities to educate a new breed of engineer more adaptable to our changing technology—the kind of engineer we are really desperately short of today.

Educational Trends

As I sense educational trends at present, we are to witness further efforts to exploit the vertical organization of education whereby the professional and the general are carried along in parallel with fewer discontinuities between the freshman year and the graduate and professional degree. New programs are under way in other professional fields, which may hold useful lessons for the education of scientists and

engineers. The new medical-school program at Western Reserve is a striking example, with its organization along functional lines rather than traditional departmental lines.

It is heartening to hear so much stimulating discussion about new approaches to professional education, and I think it bodes well for the future quality of our technology that some of the new ideas are originating in the engineering schools.

Whether one agrees or not about these particular concepts of engineering education, the ferment they reflect is important to the urgent task of maintaining and augmenting the quality of our science and technology and of educating professional engineers with a reach and grasp equal to the performance expected by our society.

A COMPREHENSIVE PROGRAM

In concluding these observations about engineering education, I wish to stress the importance of more variety, differentiation, and innovation in our system. We need more graduate study in engineering but we also need more technical institutes and junior colleges. We need more stress on science in the liberal-arts colleges but we also need the kind of undergraduate program represented by our engineering schools, where a sound general education is achieved in the environment of a professional school.

In undergraduate education of all kinds we need a differentiated system with institutions specializing in accord not so much with subject matter but with the standards of intellectual performance expected of their students. Whether undergraduate education is obtained in a liberal-arts college or in an engineering school, it should be fundamental and never narrow. All these goals and concepts are important in attracting enough top talent into science and engineering and in achieving the quality of professional achievement these great professions must have.

Excellence Is Never in Oversupply

I venture to express two hopes. I hope we keep in mind the possibility that a drop in business activity or in the volume of defense development or production could reduce the demand for run-of-the-mill engineers and scientists. Jobs temporarily might be hard to come by. Such adjustments, however, would not, except temporarily, reduce the demand for superior men; excellence will never be in oversupply for very long.

Second I hope we do not set as our goal an academic numbers' race with the Russians. The Russian educational system serves the state, ours the individual. They are highly specialized in their scientific and engineering education, and we are trending toward more fundamental generalized education, especially at the undergraduate level. Our objectives and our trends are more likely to serve our nation well and to give us the scientific and technological strength which will be indigenous and therefore in accord with our special qualities and ideals. Our goal should be to meet our own indigenous needs superbly well and not to engage in a numbers race.

And now having reviewed some of the ways whereby education must respond to our manpower needs, I come finally to the consideration of those attitudes and values now current in America which complicate our efforts to increase our ranks of scientists and engineers. In these attitudes may be found some of the underlying and less obvious causes for our failure to increase the numbers in these fields in proportion to the increase in national demand.

ANTAGONISM TOWARD SCIENCE

We note today evidence of a surprising amount of fear of science and of a misreading of what science really is.

Some of this adverse reaction arises from anti-intellectualism, from the disdain and distrust toward the learned man and the realm of reason which defaces the surface of our mid-century period like the tropic fungus which blemishes the polished surface of optical glass. Some of the aversion has grown out of the part which science has been called upon to play in the development of weapons.

Antagonism toward science and engineering has also been engendered by a feeling that they are wholly materialistic and antihumanistic. Even in this age of science we have residual legacies from the conflicts which swirled about great innovators like Roger Bacon, Galileo, and Darwin, and other discoverers. In fact, there is some evidence that we are in a period of fresh reaction against science. Underlying this reaction is one of our great educational failures, the failure to find effective ways of communicating the meaning, the method, and the spirit of science to the nonscientist—a failure for which responsibility must be shared by both the humanist and the scientist. Valiant efforts to take the nonscientist into the arcana of science have been made, such as Conant's program at Harvard and Hilderbrand's at Berkeley, but the problem is still unsolved and is still receiving inadequate attention and creative effort.

Thus the condition of intellectual separatism remains as a deep fault marring our terrain of scholarship. Robert Oppenheimer, in an address in 1953 (The Scientist in Society) gave a superb report of this condition. "I have a great anxiety," he noted, "that our educational directions, far from making us a part of the world we live in . . . may be even moving in the opposite direction . . . We live in the world very much affected by science, and even our thinking caps, and our ideas and the terms in which we tend to talk about things, the notion of progress, the notion of a fraternity of scholars and scientists which is so familiar to a Christian life and which has a new twist because of the spread of science—all of these we can see originally at a time when science was understood by men of affairs, by artists, by poets.

We live today in a world in which poets and historians and men of affairs are proud that they wouldn't even begin to consider thinking about learn-

ing anything of science, regarding it as the far end of a tunnel too long for any wise man to put his head into. We therefore have, in so far as we have at all, a philosophy that is quite anachronistic and, I am convinced, quite inadequate to our times . . . Far more subtle recognition of the nature of man's knowledge and of his relations to the universe is certainly long overdue, if we are to do justice to the wisdom which our tradition has in it and to the brilliant and ever-changing flower of discovery which is modern science."

This attitude toward science is described more bluntly in academic circles by well-worn observations. One of these notes that the scientist knows nothing of the liberal arts and regrets it while the humanist knows nothing of science and is proud of it. The other reports an incident in a liberal-arts faculty meeting. When a student named Cicero was reported as having flunked Latin, everybody laughed, but when a student named Gauss was named as having failed mathematics, only the science professors laughed.

This drawing away from science is related to an attitude of antagonism and fear with respect to scientists. The old cliché about the expert is applied to the scientist. The scientist, it is repeatedly said, should be on tap but not on top. He thus is considered to be merely one of the hired men who has no business doing anything but what he is told to do in the field of his specialty. I have heard no statement that the lawyer or banker or economist or production specialist should be on tap but not on top. I do not imply that the scientist has any right or unique qualifications to be on top. I am disturbed by the attitude that, because a man is a scientist, he is disqualified for public or private administrative responsibility even though he may be qualified.

This attitude reflects something wrong in the relationship of the scientist to society and in society's current estimate of the scientist.

Professional Parochialism

I think that the scientist and engineer are themselves partly to blame for the manner their function in public affairs has been derogated. They have tended too much to professional parochialism. They have been preoccupied with their own trade secrets, too little concerned to communicate these secrets except to each other so that the public misunderstandings about science and technology can be diminished by facts and not aggravated by mystery.

Humanist Also at Fault

But I also feel that the humanist has a responsibility for this hurtful condition. There is still too much of the separatist spirit among the lower reaches of the humanists, too much facile criticism of science as materialistic, too much envy of the scientist for his intellectual achievements, too much protesting that only in the liberal arts can the true gospel of man be found. There has been a tendency to make the scientist the scapegoat for the ills of the modern world.

Our colleges and universities must share a heavy responsibility for this separatism, for they have too easily acquiesced in protective tariffs for intellectual vested interests. Is it not true that a spirit of snobbery on the part of both scientists and humanists, each derogating the other, is one of the most virulent forms of antihumanism? I feel so. It is the great humanistic responsibility of our colleges and universities to stress the kinship, indeed the unity, of all knowledge, and to ease the vested interests and snobberies which sometimes appear among learned men. Objectivity, for example, is not the exclusive monopoly of science, nor humanism the tight monopoly of the liberal arts. In these parlous times we need to remind ourselves of this and to seek to develop more sensitive couplings interconnecting the sciences, the social sciences, and the humanities. We need to remember how the great humanists of Greece, of the Middle Ages, and the Renaissance helped to create an intellectual and spiritual environment and attitude benign to the development of modern science. As Crane Brinton observes in *Ideas and Men*, "Science needed not merely an interest in material things; it needed the intellectual apparatus to devise the incredibly complex ordering of things we call science; it needed above all the long training in the use of reason afforded by the Greek and medieval philosophy and theology our innocent logical positivists like to deprecate."

Humanism is no less important today as an ally of science in the great coalition of learning we seek. The humanist is one of the principal architects and custodians of the benign environment which science requires for its success. The beauty the great humanist creates or makes us aware of, the perspectives of history he reveals, the "vision of greatness" he sets before us, his search for the first-rate in living, the eternal questions he asks—all these activities help to create the great society and the great men which science requires to flourish.

The Scientist's Contribution

We need also to reiterate how the great scientists have broken shackles of ignorance and superstition, given new leads in the social sciences, profoundly influenced and enriched the philosophy and the understanding of men and thereby given a new depth and reach to humanism. As George R. Harrison has eloquently written: "There is no evil, no inhumanity, in the primary task of science, to forward man's love and desire for truth. An increased awareness of truth has often made men uncomfortable but seldom has it made them less human. Science increases the areas of spiritual contact between man and nature, and between man and other men." When I hear our schools of science condemned as citadels of materialism and our liberal-arts schools held up in contrast as the sole custodians of the liberal spirit, or when I hear that our schools of science have the only sound approach to education, I cannot but feel that the true spirit of liberalism and science is forgotten and the symbiotic relationship between the great fields of learning ignored.

The liberal arts of our time cannot be liberal if they reject or disdain science and technology. Thus science and technology cannot fulfill their responsibilities if our scientists and engineers lack the humanistic quality which has been ascribed to the Athenians—the art of making gentle the life of mankind. In our schools of science and engineering we must seek to cultivate this quality.

For Better Understanding of Science

Scientists have an obligation to make this true character of science better understood, not by an arrogant advocacy of science and technology as the only objective means to increase our understanding and well-being, but by the balanced and tolerant presentation of science as one of the powerful means by which man can increase his knowledge and understanding and still remain humble and ennobled before the wonder and the majesty of what he does not understand. When thus perceived and practiced, and when not misused for ignoble ends, science and engineering are a major means for "making gentle the life of mankind." If science can thus appear in its true colors and thus be recognized, we will have accomplished a major requirement for attracting enough first-rate minds into science and for maintaining a vigorous and advancing technology.

A practical procedure for mass-producing plastic springs has been developed by the National Bureau of Standards in work sponsored by the Army Ordnance Corps. The springs are molded by drawing glass fiber-reinforced resin through vinyl copolymer tubing and wrapping the loaded tubing in a helix around a mandrel. After curing in an air-circulating oven, the tubing is removed, leaving a solid plastic spring reinforced with glass fibers.

CAPTAIN R. E. W. HARRISON, USNR, Retired

RUST—THE IMPLACABLE ENEMY

THE AUTHOR

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INTRODUCTION

In well managed commercial activities it is the duty of the man in charge to protect the investment of the stockholders by taking all precautionary normal and routine action as comes within his purview, and then seeking any special authority needed, when unusual measures are required to protect the investment.

Usually the official in charge thinks mostly in terms of dollars when he reviews his stewardship —first, did he make a profit in that last fiscal year? —secondly, did he properly maintain the plant and property which earned that profit?—and last, did he put into being, prudent policies which preserve and protect the investment during the years ahead?

All these considerations find a place in the thoughtful management reviewing process—whatever the activity be—commercial or governmental, State, County, or City authorities, where plant and property are in use or needed standby status.

It is a strangely true fact, however, that from the calculations of many managers, there is omitted proper consideration for a most important element of hazard to the investment—i.e., attrition on the value of the machinery due to a never ceasing process of oxidation.

This is the iron age in which we live—most of the plant equipments which we use are made of iron or its derivatives—and iron, basically, is as completely vulnerable to rust, as is wood to termites—the nonferrous metals, likewise, have their ever busy "worms."

So it not infrequently happens that the General Manager goes on his way—year after year—paying adequate dividends to his stockholders and expanding their plant—but blissfully ignorant of the fact that their original equipment has eroded to the point where no ordinary yearly depreciation fund will pay for the inevitably required replacements. In consequence, a special Board Meeting—a deep dip into the company's reserve funds—maybe some lost production—and maybe the boot for the manager who failed in his trust. In those cases where this manager is an officer of the Armed Forces, failure to wage relentless war on the elements which rot out his equipment can have dire consequences, not only for the manager directly concerned, but also on the country as a whole—a veritable vale of tears for the fighting men whose ability to fight an enemy, and to defend themselves, is jeopardized—also for that oft forgotten person, the poor taxpayer.

Scare talk some will say—well, at a modest estimate American Industry loses each year $5-billion

because of avoidable corrosion—some sound authorities even say $8-billion, which in any man's language is a sizable sum to throw down the drain.

Inevitable!—did you say? Well, recent excavations near an ancient Roman city in England unearthed iron knives and hobnails in perfect preservation although they are 2,000 years old. Chemists have analyzed the metal and found that corrosion was stopped by a coating on the iron which they identified as tannin, a compound used in tanning leather.

What then to do about our corrosion problem?

The answer appears simple—that is, if a superficial solution be acceptable—the trouble is, however, that the ill we seek to cure was generated in the first place by someone in authority who dismissed a basic problem because his shortrange spectacles could not reach out far enough to see the trouble that his folly was creating.

Basically all our commonly used metals are under corrosion attack from the time when the ore is pulled from the ground. It is ashes to ashes, and dust to dust with them eventually, just as it is with our general manager who would have died as a baby if his doting mother had not swaddled him against the ever cruel attacks of the atmosphere.

Proper care exercised at birth, infancy and all through life, are an obligation if a piece of machinery is to live out its proper life span. One circumstance there is which helps—metals, like children, break out in easily discernible spots when they are ill—it may be measles for junior, but it is rust on metallic surfaces—and it can be the beginning of ruin for the man responsible for that ship—that locomotive—or that valuable plant in which his trusting stockholders or taxpayers sunk their savings.

The answer is *not* simple—but like all such problems, this one, also, will yield to analysis, and the General Manager, if he be truly conscientious, will protect the interests of those who hired him, by seeing the analysis through to a conclusion, and being guided accordingly.

All mechanical structures—houses, ships, machinery, locomotives and the rails they run on—are engineered to survive a period of time estimated as an economic life, it being presupposed that there will be no undue falling off in use efficiency during that life, otherwise economic feasibility or earning power will fall off, and the project will fade out of existence from sheer monetary anemia.

Good designers weigh the two curves of economic and use efficiency most carefully, and the most successful are those who devise a design which satisfies both demands at minimum first cost. It is, however, at this point where the Achilles heel can be born, because the designer, when computing his curves, presupposes an adequate scale of maintenance, a presupposition frequently as stable in concept as a house built on shifting sands, or a maid's whim in the springtime.

Sometimes—in fact all too frequently—when the economics of the case will stand a relatively high first cost—the designer beats the maintenance man to the draw, by calling for stainless and other corrosion resistant steels, and other metals recognized as having a minimum rate of decay under the worst possible operating conditions—but—all economic balance sheets must take into account an interest or service charge on capital investment—and this charge can then be so costly, when the highest cost raw materials are used, that the balance sheet shows no profit balance and the enterprise or project is, therefore, without financial and economic feasibility.

The one potent exception is found in military equipment—here, good maintenance practice in the field is often impossible—so—metallurgical specifications are based on maximum performance for the longest time obtainable, or as dictated by carefully anticipating required hours of usage at maximum performance efficiency.

To clear the air—consideration in this thesis has been given first, to those cases where Economic and Military necessities have resulted in the use of the least corrodible metals.

Now lets consider the other 95%—i.e., the vast tonnages of machinery and other plant equipment where maximum dollar earning capacity during economic life span, can only be obtained by unremitting intelligent maintenance predicated on technically sound experience. Remember, we are still tender on the subject of that stockholder's dollar, and we want our General Manager to keep his job—something which he definitely will not do if he has the responsibility pinned on him for an undue share of that annual loss of $5-billion traceable to failure to recognize rust as the implacable unremitting enemy.

From the entirely practical viewpoint—sound preservation practice starts in the foundry and the rolling mill—long before the bits and pieces reach the machinery builder's shops. Ingrained rust and hydroscopic dirt, as well as that totally unnecessary veil known as mill scale are handicaps of ignorance or indifference, or both, built into Junior's career of usefulness—just as some youngsters are projected into the world with defective hearing or poor eyesight—the only difference being that the former handicaps are unnecessary, and acceptance is due to ignorance and indifference—long accredited and well known by those euphonious names of trade practices, and trade standards.

Well, we know the virtues of clean degassed metal —also the proven advantages of inorganic molding materials—but steadfastly we—or that is, too many of us—stick to archaic practices—and send to the fabricators the fruits of our sins in the form of rust and scale pitted castings, forgings, weldments, plates and shapes. Junior already has the chickenpox, and, oh mother, if you only knew it, that child has been mishandled from birth by someone with unclean hands.

We—the people—or rather the engineers—could

get more than a little indignant about Junior's poor start in life, but, well must we remember that established practices—both good and bad—die hard. So —where do we go from here—or there?

We shotblast and chip out the holes left by the mill scale and foundry dirt, and surgically we get down to virgin metal. Then before the damp air can go to work (we hope), the surface is sealed off (we hope) for life, or at least until the next drydocking.

In passing, however, one big and important difference in cases should be noted—Junior's pock marks will fade with the passage of time—ours, if we do not watch them, will grow wider and deeper every day, and eventually, as focal points of infection, they will ruin us. Rust—the implacable enemy—is always ready to step through an open door, and a pit mark or cavity caused by removal of mill scale or foundry dirt immediately becomes the starting point for ruinous infection unless corrective measures are prompt and thorough.

THE ECONOMIC BALANCE

If we assume that all the above mentioned factors have been accounted for—properly weighed—and a true balance struck—we find that the great bulk (about 95%) of all U.S. industrial structures are made from corrodible materials, and that sealing them off against attack is perpetually mandatory throughout the economic life of the structure.

The work of striking off a valid balance sheet is not easy, and this author well recalls a case where $3-million had been voted to finance a certain bridge where the engineers were called on to present their proposals two ways—standard structural steel, and alternatively prestressed concrete design. First contract prices tendered were close—the prestressed concrete job being the slightly higher of the two. Despite this, decision was made by the buying authority in favor of concrete, because of a record of much lower cost of maintenance during anticipated life. Concrete structures require some maintenance care, but generally over a period of fifty years the cost will be much less than that for well maintained steel, Q.E.D. Every case, therefore, must be weighed and decided on its individual dollars, conditions and merits.

SYSTEMATIC MAINTENANCE OF STEEL STRUCTURES

In essence—assuming of course that we have correct engineering design—the problem is that of sealing off the structure against the attacking forces—moist air, salty, chemical laden, or fresh, being the most potent.

The chemistry of protective coatings designed to do the sealing is fairly simple—however, the problem of securing an effective seal at lowest cost and effective for the longest time, in the face of conflicting claims by numerous manufacturers, is extremely difficult to resolve unless the buyer making the decision is backed up by access to a great deal of experience, highly specialized training and accurate records—facts, rather than just mere words.

In the Armed Forces, where quality of equipment frequently determines military effectiveness and even survival of combatants, the correct decision is particularly demanding and can only be arrived at after field tests duplicating actual combat conditions. Military Public Works structures are often in the same sensitive category.

Commercial industrial structures are another matter and their projected useful life span—also the degree or quality of systematic maintenance—frequently become subject to widely variable yearly budgets, which in turn, are the product of institutional policy tuned to profits and markets.

All this adds up to a strong economic desirability of higher investment in initial protection and sealing —it having been definitely proven that it is most economical in the long run to start a new structure off with a maximum of protection.

In those cases where there are insufficient funds available to both thoroughly sandblast the structure and to thoroughly seal it off from the elements, it is better practice to put the available money into the best seal procurable, for to thoroughly clean the structure and then imperfectly seal it is simply inviting trouble—like Junior washing his cut finger in a puddle of dirty water.

WHAT MAKES THE PERFECT SEAL?

Maximum wetting ability on the part of the sealing vehicle is mandatory—otherwise the seal will be superficial and broken in places—often in those locations where an attack is most deadly in its weakening effect on the structure. The electro-chemical action of oxidation at unprotected spots is actually accelerated by the presence of the seal on the readily accessable surfaces—current density is increased and deterioration at the unprotected spot is proportionately accelerated—the phenomenon is inescapable—hence the wetting ability of the vehicle determines the effectiveness of the seal as a whole.

It is also necessary that the seal be durable and elastic enough when dry to stretch and contract to whatever degree the structure moves, expands or shrinks, under the worst expectable weather and load conditions.

Oldtime sea-faring men had their own rust prevention processes; a barrel of raw fish oil, mixed with graphite was used to cover all the exposed rustable metal surfaces and this relatively crude, but quite effective measure, proven over decades, served to firmly establish the fact that wettability is all important.

Fish oil, because of its low surface tension, drives out air and moisture from interstices so thoroughly that a protective coating can be established even on a damp surface. It is not even necessary to remove all rust, however, rust scale, mill scale and any previous coating not sticking tight, or under which rust may be forming, should be removed. Actually the

fish oil then envelopes the particles of remaining rust and makes them a part of the primer coating.

The foregoing is of the very essence of the technique of preservation of metallic surfaces, and actually it performs healing service for metal structures exactly similar to that which it does for the fish from which it was extracted. Furthermore, having regard to its source, it is not surprising that this oil expands and contracts without break in the film whenever environmental changes occur.

As is natural, it takes longer for this type of oily vehicle to dry; however, the time is not excessive (varying from four to twelve hours) and is but a minute fraction of time, when it is considered that this valuable natural product will do its work reliably as a sealant for from four to seven years, which in most normal maintenance, is about twice as long as the next best vehicle.

Colors present no problem. There is one disadvantage, however, which accrues to the manufacturer who pins his flag to this vehicle, and that is the longer drying time involved makes the coating unsuitable for use on machinery made on a mass production line. Furthermore, the addition of dryers is not feasible, in that they subtract from the very virtues which make the coating so technically desirable.

A recently completed research project, undertaken by the Battelle Memorial Institute, has demonstrated in an unusual way the remarkable wetting and penetrative properties of fish oil.

A carefully rusted series of steel plates were coated with a rust inhibitor of the type referred to above. The vehicle had hitherto been impregnated with radioisotopes in known density—and after a suitable test interval the rusted and coated plates were honed progressively down to bare metal and a record kept of each honing, which proved conclusively that the selected vehicle consistently carried the protection all the way in through the rust down to the bare metal.

Thus we have a modern scientific confirmation of the merits of an ancient practice, to which we have added refinement but no basic change.

From earliest times of record, it has been noted that raw fish oil (as slow-drying and odorous as it was) has been used, mixed with earthen pigment, as a protective coating. There are many cases on record of raw fish oil and earthen colors used by the North American Indian for decorative and preservative care of his totem-pole, still in good condition an estimated 60-70 years later.

The following extracts from the Battelle report of May 10, 1955 depict an interesting method of attack on a problem which has been with us ever since the genesis of the Iron Age:

> The objective of this research program was to develop a method of determining the degree of penetration of the product into the rust layers of steel specimens. To attain this objective, a plan of research was agreed upon as follows:
>
> (1) Identify one or more of the major chemical constituents in a fish-oil-based vehicle supplied by the Sponsor
> (2) Synthesize this constituent, using radioactive C^{14}
> (3) Add this C^{14}-labeled constituent to the fish-oil vehicle, thereby yielding a radioactive fish-oil vehicle which could be processed, by the Sponsor, into a radioactive coating equivalent to the Sponsor's standard product.
> (4) Apply the radioactive coating to rusted steel specimens and demonstrate the degree of penetration of the product into the rust layers by autoradiographs or other radiochemical techniques.

A radioactive fish oil was prepared by the esterification of C^{14}-labeled glycerol and fish-oil fatty acids obtained by saponification of the original fish oil. This oil was converted into the vehicle and appropriately blended to yield a radioactive primer coating.

The radioactive product was applied to rusted steel specimens. The degree of penetration of the radioactive component of the product into the rust layer was determined by a radiochemical lapping technique. A measurable amount of radioactivity was detected wherever rust was observed on the steel specimens, thus indicating that measurable quantities of the fish-oil penetrate the rust layer of rusted steel to the steel surface.

The Corporation manufactures and markets anticorrosive protective coatings based on a processed fish-oil vehicle. It is claimed that the vehicle portion (containing the processed fish-oil) of these products can penetrate the rust layer of rusted steel. The Corporation is interested in determining the degree of penetration of their product into rust layers. Attempts to obtain this information, using X-ray techniques, had not proved successful. It was subsequently agreed that preparation of a radioactive vehicle of the same composition as standard vehicle might provide the means for determining the degree of penetration of the product into rust layers on steel. In each method, the depth of penetration is indicated by the concentration of the radioactive components in the protective coating and rust film. In the autoradiographic technique, a photographic emulsion is exposed to a cross section of the rusted steel specimen that has been painted with radioactive coating. The extent of penetration of the radioactive component is indicated by the relative density of exposure of the photographic emulsion. In this particular case, preliminary experiments indicated that the concentration of C^{14} in the coating was too low to produce an autoradiograph suitable for reproduction. For this reason, application of the autoradiographic technique appeared questionable. Several cross sections of Specimen 5 were prepared for autoradiography, however, to determine if some reaction might be obtained over a 2-month exposure period.

The lapping technique appeared to be much more promising, in view of the low concentration of C^{14}. In this technique, the radioactivity of the surface of a painted specimen is determined, then a thin layer of the surface is removed by lapping, and the radioactivity of the newly exposed surface is measured. This procedure is repeated until the protective coating and rust are removed and a bare steel surface remains. The concen-

tration of the radioactive component in layers of the protective coating and rust film at various depths is thus determined.

Lapping Procedure

A specimen was mounted in a lapping fixture that made possible controlled removal of the surface layer. Crocus cloth was used as an abrasive. Micrometer measurements were made before and after each lapping cycle to determine the exact thickness of the layer removed.

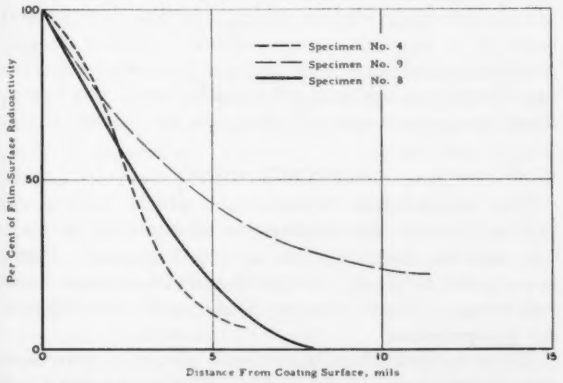
Demonstration of the Penetration of Radioactive Coating into Rust Layers on Steel Specimens

Discussion of Method

Radioisotopes have been used extensively in recent years in diffusion and penetration studies. A number of techniques are available for tracing the penetration of a radioactive component into a nonradioactive matrix. Two alternative methods, autoradiography and lapping, appeared applicable to the problem of demonstrating the penetration of the vehicle component.

Determination of Radioactivity of the Surface

Radioactivity measurements of the specimen surface were made with both an end-window Geiger-Mueller tube and with a gas-flow proportional counter. Because of the low energy of the β particles emitted by C^{14}, this radiation is readily absorbed by matter. The β particle range in a product-coating film is approximately 2 mils. Since it was desirable to measure the radioactivity of a 0.5-mil-thick surface layer, the measurements with a Geiger-Mueller tube were found more suitable. With this detector, only the most energetic β particles emitted from the upper layer of the coating and rust film were measured. As the coating and rust layer was removed by lapping, the residual radioactivity decreased and the precision of measurement with the Geiger-Mueller tube also decreased. It therefore became necessary to use a gas-flow proportional counter to verify the presence of the radioactive component in layers close to the bare steel surface where the radioactivity was relatively low. When using this counter, the specimen was inserted directly into the radioactivity detector and all β particles emitted from the coating and rust surface were counted.



Radioactivity as a function of depth in protective coating and rust film for samples with two coats of protective coating.

THE RADIOACTIVITY OF VARIOUS LAYERS OF THE COMPOSITE SPECIMENS

Distance from Coating Surface, mils	Radioactive Vehicle in Layer, per cent of total	Remarks
0–0.5	18.6	Coating film
0.5–1.0	17.3	Coating film, some rust
1.0–1.5	14.9	Coating film, some rust
1.5–2.0	12.0	Coating film, some rust
2.0–2.5	9.5	Mixed, rust and coating
2.5–3.0	7.4	Mixed, rust and coating
3.0–3.5	5.8	Mixed, rust and coating
3.5–4.0	4.6	Rust, some coating
4.0–4.5	3.7	Rust, some coating
4 5–5.0	3.2	Mixed, vehicle, rust, and metal
5.0–5.5	2.9	Mixed, vehicle, rust, and metal
5.5–6.0	0.0	Metal

CONCLUSIONS

There has been made available a protector of metal surfaces *which works*—a major step forward in the technology of metal protection. However, none of the research so far has indicated that it has been possible to properly protect a metallic surface unless every trace of chloride has been removed from the surface before applying the protective coating.

The implications are inescapable if an operator fails to decontaminate metallic surfaces of salt brine before proceeding to apply a protective coating.

Further research along these lines is being undertaken, and it is expected that much valuable data of special interest to Naval Engineers will become available. For the time being, at least, it has been proven that while we can penetrate all rusts down to base metal, the good results desired cannot be counted on when a chemical element which is the mainspring of the trouble is entrapped in the protective coating.

In those cases where a badly mottled surface with rust spots spaced at frequent intervals is revealed, it is fair to assume that the basic cause of this failure can be traced to imperfect cleaning methods, used before the first protective coating was applied.

A retired naval officer, recently back from a visit to a number of naval ships, records that after a number of years absence from the sea, he was surprised to find that rust fighting duties of the crew aboard a naval ship seemed to demand about as much time today as was needed thirty-five years ago.

While this in some measure could be attributable to the vastly increased use of electricity aboard ship with its concomitant nuisance of electrolysis, the fact remains that much needs still to be done to adequately protect this nation's first line of defense against its implacable enemy, rust.

"AUTOMOTIVE INDUSTRIES"

NEW CONCEPT OF DIESEL COMBUSTION

ACKNOWLEDGEMENT

This article was written by Dr. P. H. Schweitzer, Head of Diesel Research, Pennsylvania State University, and was published in "Automotive Industries."

THE NEW MAN WHISPER engine [1]* hit the industry with an impact, but the underlying combustion theory largely failed to penetrate the engineering consciousness. The reason for this is not so much that the new theory is too difficult to understand, but rather that it is too upsetting. The mind instinctively tends to close rather than to accept its implications.

From the time the diesel engine was invented, thought was always concentrated on mixture formation. It can also be truly said that the improvement in mixture formation was paralleled with diesel engine progress. Early slow-speed diesel engines used air injection first and a multiplicity of nozzle orifices later when solid injection was adopted. The high-speed diesel engine became a success with the introduction of the precombustion chamber by L'Orange in which the initial combustion of a small amount of the fuel helped to disperse the rest. This was followed by the swirl chamber engine of Ricardo, and the air-cell engine of Lang. In every case artificial means were used to disperse more uniformly the fuel which was already finely atomized by a high-pressure injection nozzle. Auxiliary chambers were accepted as a necessity although they had higher fuel consumption because of their higher heat loss and "pumping" loss.

The high-speed direct injection open chamber engines could not make the grade until the invention of the swirl and squish. A violent air motion was needed to disperse the fuel uniformly in order to prevent the mixture from being overrich at one spot and overlean at another spot during combustion. Did we need anything more to be convinced that perfect distribution makes a perfect diesel engine?

True, the engines with the most perfect atomization and dispersion still knocked and smoked. This was attributed to the circumstances that the atomization and dispersion was still not perfect enough. In order to refute this theory, MAN's Dr. S. Meurer built an engine where distribution as photographed was almost perfect. This engine with the most perfect mixture knocked and smoked more than the others.

When Dr. Meurer made this experiment he already knew that the accepted theory of combustion is false. Concentrating on the physics of the mixture formation, the engineers ignored the chemistry of the combustion.

Combustion was regarded merely as an oxidation process. In the process the hydrogen of the hydrocarbon molecule burns to H_2O and the carbon to CO_2 perhaps after some intermediary stages. What actually happens is quite different. Combustion reaction is accompanied all along with pyrolysis or cracking of the molecules. Cracking of the hydrocarbon takes place in the absence as well as in the presence of oxygen.

An early product of this cracking is hydrogen which burns explosively with knock. The end-product is often pure carbon which is a slow burner and some of it appears as soot. Hence exhaust smoke. No mechanical process of mixture formation can prevent this sequence. Judged from Meurer's discovery, diesel engineers were all along on the wrong track.

COMBUSTION THEORY

This combustion theory, by which carbon is formed during the combustion of hydrocarbons, is less new to chemists than it is to engineers. There is no point to going into the details of various theories because their common denominator is sufficient for the purpose.[2]

When hydrocarbon burns, two chemical processes are taking place side by side: oxidation on one hand and pyrolysis or thermal decomposition, commonly called cracking, on the other hand. When exposed to high temperature and pressure, the molecules break into atoms. The ease with which molecules break is indicated by their bond strength. It takes

* Numerals refer to list references.

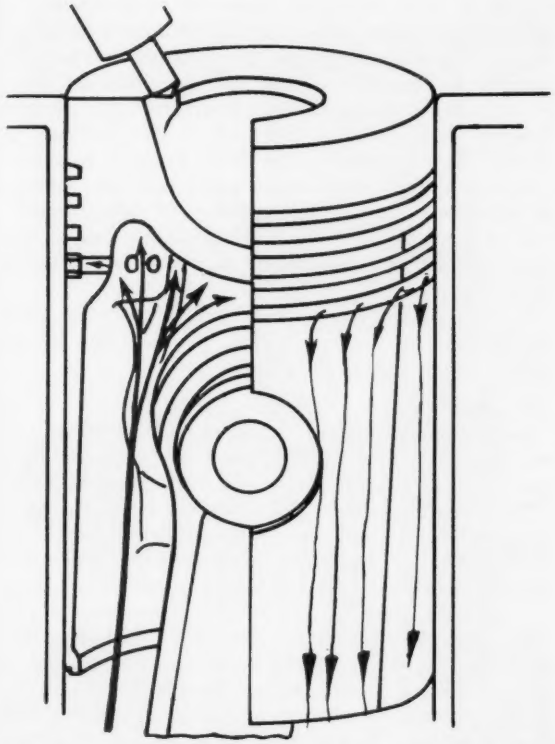


Figure 1. Cross-section drawing showing the flow of oil around the piston.

80 kilocalories per mole to split a single-strength carbon molecule, 150 kilocal/mole for a double-strength carbon molecule, and 200 kilocal/mole for a triple-strength carbon molecule, (C−C) =80, (C=C) =150, (C≡C) =200. But to split a carbon-hydrogen molecule takes only 100 kilocal/mole, (C−H) =100. So hydrogen atoms will split off and may oxidize before double-strength carbon atoms crack. When heavy carbon atoms crack their oxidation is delayed by circumstances that will appear later.

Cracking is taking place with or without the presence of oxygen. In the former case oxidation reactions compete and interact at every step with thermal decomposition. Thermal decomposition is promoted by high pressures and temperatures. However, even at low-temperature oxidation of hydrocarbons, decomposition predominates over polymerization, unless the primary products isolated are lower hydrocarbons, aldehydes, alcohols, ethers, peroxides, etc.[3] Formaldehyde and methyl alcohol decomposes mainly to CO and H_2, consequently no carbon appears in their flame and they cannot be made to smoke. All other hydrocarbons develop carbon at least at an intermediate stage of the combustion process and in some cases part of the decomposition reactions proceed to this phase *before* any oxidation takes place.

However, what kind of flame develops after the early cracking of the hydrocarbon depends largely on amount and distribution of the oxidant present.

The flame of a wick lamp or a candle is typical of what is called a diffusion flame. The oxygen gets to the reacting hydrocarbon molecules from the outside and through diffusion only, which is a rather slow process.

In the presence of a normal amount of air, the kerosene in a wick lamp burns without smoke. But does this mean that the combustion is an oxidation process purely? If it were, the flame of the lamp would be pale blue instead of bright yellow. It is the glowing carbon particles which give the flame its yellow brilliance, and the incandescent carbon particles are of a *solid state*. These particles are small but much larger than a molecule. In certain diffusion flames decomposition to carbon is complete before the oxygen zone is reached.[4]

The "premixed" flames, like a Bunsen burner, are of different nature. If the gas-air mixture contains sufficient oxygen after ignition for complete combustion, oxidation processes probably predominate over those of pyrolysis, but C_2 bands still appear in the emission.[5]

In premixed flames of a wide range of hydrocarbons uniformly mixed with air, the *carbon forming* point is at mixture ratios of 130 to 140% stoichiometric (rich)[6], and the smoking point is still higher.

Figure 2. This diagram shows the direction of the fuel spray and the manner in which the fuel is spread over the walls of the combustion chamber. Temperature of the wall is controlled. A true burn of fuel, instead of a detonation, is accomplished by Dr. J. S. Meurer's revolutionary theory.

This indicates that in gaseous combustion of a slightly rich mixture the excess carbon oxidizes to CO and no carbon appears in the flame. In somewhat richer mixtures carbon does form but is consumed by the flame before any part of it is released as smoke. A further enrichment of the premixed flame causes smoke to appear, but the mixture ratio then usually exceeds 160%.[6]

The flame in a carburetor engine is somewhat like a premixed flame, while in the diesel engine it is more like a diffusion flame. True, the fuel is atomized but the drop size is of the order of 50 microns and contains some 10^{14} molecules. Only a small portion of these molecules are on the surface of the droplets, the rest depend upon evaporation and diffusion for access to oxygen. Diffusion is a relatively slow process while thermal decomposition accelerates at an exponential rate. So oxidation is unable to keep pace with the thermal decomposition which leads to formation of carbon nuclei which grow into particles of soot, varying in diameter from 0.1 to 1.0 micron.[6] Part of that carbon will burn during combustion, but part of it will fail to oxidize and will be released from the luminous flame as soot, which is either pure carbon or predominantly carbon. Soot either leaves the engine in the form of exhaust smoke, or becomes deposited on the combustion chamber surfaces as lacquer, coke, and other residues.

We may conclude that oxygen deficiency is not the primary cause of smoke. Even with a considerable excess of oxygen during combustion smoke may appear if:

1. the hydrocarbon molecules are exposed to cracking temperature (750—1,000° F.) for a sufficient length of time, *and*
2. one of the ultimate cracking products is carbon, *and*
3. that carbon fails to oxidize completely before it leaves the flame region.

On the other hand, we may have a deficiency of oxygen; in other words, burn an overrich mixture and still have no smoke if:

1. the hydrocarbon is of such composition (as methyl alcohol) that the products of thermal decomposition do not include carbon, *or*
2. no solid carbon forms as the excess carbon oxidizes into CO, *or*
3. the carbonaceous end-products of the thermal decomposition completely burn inside of the flame.

While shortage of oxygen is not the primary cause of smoke, such shortage promotes smoke formation so powerfully that smoke is generally associated with oxygen deficiency.[7] Oxygen deficiency may be overall as in a premixed flame or in a gas engine, or only local as in a diffusion flame or a diesel engine. If the amount of oxygen present is insufficient to oxidize the carbon formed through thermal decomposition, or, although sufficient, the diffusion of the oxygen to the carbon is not fast enough, and is not being helped by the continued presence of hydrogen or dissociating water vapor, smoke will form depending on the circumstances. A probable mechanism appears to consist of initial dehydrogenation steps, or stripping hydrogen atoms from the hydrocarbon skeleton by successive reactions of free radicals or atoms.[3] This is followed by decomposition to acetylene and hydrocarbon fragments which then undergo simultaneous polymerization and dehydrogenation to form smoke.[8] A considerable amount of this finely divided smoke actually burns or is consumed by the flame.

Knowing how smoke and carbon residues form should help us prevent it. This problem can be attacked from various directions.

FUELS

Some fuels are smokier than others, and the fuels which are smokier in diesel engines are ordinarily also smokier in gas turbines and even in wick lamps.

The most important fuel property is its chemical composition. High carbon-hydrogen ratio and high carbon bond strength promote smoking tendency. Formaldehyde (CH_2O) and methyl alcohol (CH_3OH) never smoke, paraffinic fuels smoke less than naphthenic, and these less than aromatics. The more readily the hydrogen atoms are removed as compared to the breaking of carbon bonds, the greater the probability of smoke formation. Heavy fuels smoke more than light fuels and a more compact molecule has a higher smoking tendency than a loosely built molecule.

Another fuel property which influences smoking tendency is volatility. The more volatile fuel vaporizes faster which is essential to permit adequate oxidation to take place. The more the oxidation process can keep pace with the pyrolysis, the less carbon will form and the carbon which does form has more chance to oxidize and burn before it leaves the engine cylinder.

Operating conditions most conducive to smoke are, therefore, those which create a shortage of oxygen or reduce the excess air in a diesel engine: overload, altitude, clogged air cleaner, etc.[7]

ENGINE DESIGN

The greatest profit can be derived from the new knowedge in engine design. This is what Dr. Meurer did with spectacular success. He reasoned somewhat like this:

The problem is to introduce a certain amount of fuel into the cylinder and burn that fuel without noise and without smoke. Most of this fuel should burn at or near top center position of the piston to insure a good thermal efficiency.

The conventional answer was to atomize the fuel very finely and inject it when the piston is nearing top center position in such a manner that the spray will reach every cranny of the combustion chamber. By doing just that Meurer found that the engine was noisy and smoky. It is now easy to see why.

Fuel was injected into the engine cylinder and

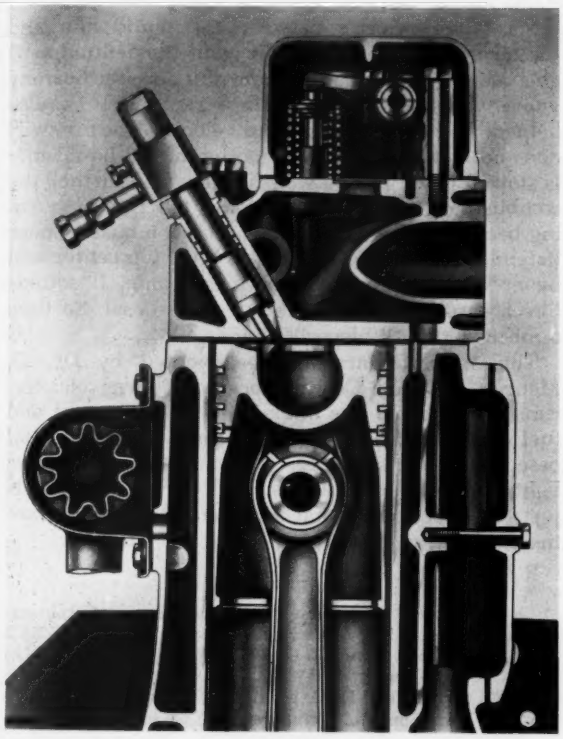


Figure 3. This cross-section of the M.A.N. Whisper engine shows the spherical combustion chamber in the piston crown and the disposition of the injection nozzle.

found air in it with a pressure of about 600 psi and a temperature of about 1,000°F. When millions of droplets find themselves in such an environment they crack. Few of the hydrocarbon molecules that crack into carbon find adjacent oxygen molecules to combine with. The cracking and the ignition occur in an envelope surrounding the droplet near the liquid-vapor interface. But much of the oxygen never has a chance to get to this interface.

Making the spray finer may help but the droplets would have to be 10^{11} times smaller in volume to get them to molecular size which is obviously impossible.

A near thought is to vaporize the fuel outside and introduce it into the cylinder in vapor form. This is about what is done in a gasoline engine, but it cannot be done in a diesel for two reasons. First, because no carburetor or vaporizer can handle diesel fuel with a distallation range from 300 to 600°F. Second, even if we should get dry vapor into the cylinder it will fail to ignite by compression ignition. We must have either a spark plug or at least pilot spray of liquid fuel to ignite the cylinder charge.

If the fuel cannot be vaporized outside of the cylinder, Meurer reasoned, it must be vaporized inside the cylinder but under such circumstances that will discourage cracking. The cracking temperature is about 750—1,000° F. So the problem is how to keep the fuel cool in the 1,000° F air and make it evaporate before it becomes hot.

Meurer accomplishes this by smearing the fuel on a cool surface. The combustion chamber is formed by a hemispherical cavity in the piston which is cooled by an oil jet from underneath as seen in Fig. 1. The fuel is sprayed against the combustion chamber wall slightly downward at such an acute angle that it spreads out on the wall without bouncing off (see Fig. 2). The temperature of the oil film is above the vaporization temperature but below the cracking temperature, approximately 400 to 750° F. This is, of course, much too low to vaporize all of the fuel during a small fraction of the cycle.

This is accomplished by exposing the thin layer of liquid fuel to hot wind immediately and to hot radiation later. The fuel will then evaporate fast enough to finish combustion in time.

The one practical way to make wind in the combustion chamber is by creating an air swirl. This swirl must be of the persistent type, it must last after the reversal of piston motion. To that the air is introduced tangentially into the cylinder through "masked valve" or a "twisted" port. In this way Meurer obtains an air swirl 2–3 times engine rpm. To this he adds "squish" by keeping the clearance between piston rim and cylinder head minimum (Fig. 3), and so squeezing the air from the periphery to the center. In this manner a swirl which is 6 times engine rpm can be obtained, sufficient for fast initial vaporization of the fuel. To make most of the fuel adhere to the combustion chamber wall it is injected in the direction of the air swirl.

The remaining problem is how to ignite the charge. Combustible gases and dry vapors are reluctant to ignite spontaneous'y but they can be ignited easily by an external source. A fine spray, on the other hand, ignites readily in hot air.

One could provide a fine spray, off the combustion chamber wall, while most of the fuel is made to impinge upon it. Alternatively the very same jet or jets which are directed to the wall, by first traversing a short air gap, shed some finely atomized droplets which float in the air and ignite before they reach the solid wall. A few of these ignition nuclei are sufficient to ignite the vapor formed by the evaporation of the fuel film.

Now we have a brand new diesel combustion system which works as follows:

During the intake stroke the air enters with a directional guidance so that it begins to rotate in the cylinder around the axis. This rotation persists during the compression stroke and is even augmented near the end of the stroke by the squish produced by the small (approx. 1/32") clearance between the piston rim and the cylinder head.

The piston has a hemispherical combustion chamber with a diameter about ½ of the cylinder bore. As the piston approaches top center on its compression stroke, there exists a vigorous air swirl (approx. 6 x rpm) in the hemispherical chamber.

Some 20 degrees before top center an obliquely located injector sprays two jets at an acute angle to the wall of the combustion chamber, in the direction of the air rotation, bent a little down. Some 95% of the injected fuel impinge on the wall while some 5% become atomized and dispersed.

Shortly before the piston reaches its top center position ignition occurs in the atomized spray. The rest of the fuel, helped also by the air swirl, gets spread on the combustion chamber wall in the form of a thin liquid film about ¾ around. The hot air scrubbing this liquid film makes it begin to evaporate. It is helped by the warm combustion chamber wall which, however, must be below the cracking temperature, around 750° F minimum.

A layer of vapor forms now adjacent to the combustion chamber wall which is promptly ignited by the ignition nuclei of the atomized 5% spray. As this vapor layer burns it transfers heat to the liquid film and accelerates the evaporation. The vapor mixes intimately with the still swirling air and burns almost as soon as it is formed. Whatever carbon is produced by thermal decomposition, it is consumed in the "premixed" flame through intimate contact with the oxygen. So the fuel burns clean even with only a moderate amount of excess air without exhaust smoke and with a minimum amount of carbon deposits in the engine.

Conventional diesel engines have a pronounced combustion knock. The finer the atomization the worse they knock. The reason for this is the ignition lag. It takes 1 to 3 milliseconds for the fuel to ignite after it gets in, no matter how fine the droplets are. During that time in a high-speed engine half or more of the fuel gets in. All being in fine droplet form when one ignites all ignite. The result is excessively fast burning and rough running, referred to as diesel knock. Retarding injection relieves the knock but aggravates the smoke.[9]

The M-engine has no diesel knock. The fuel which is in the form of a liquid film will not ignite, only the 5% atomized portion. As the film successively evaporates it burns. This is a gradual process. It starts slowly because the fuel film is still cold and the relative velocity between the liquid film and the air swirl is small. Then it gains momentum as it gets along. The radiation from the already burning vapor vaporizes the fuel more rapidly. It is also helped by the increasing wind velocity. The air swirl does not get faster but the motion of the liquid film is slowed down by the wall friction. The further the combustion progresses the higher the rate of burning becomes. This helps to clean up combustion near its end. Most of the fuel ignites after top center and never a great amount at any one time. It sounds like a gasoline engine rather than a diesel. So they dubbed it the "Whisper" engine.

This revolutionary engine invented by Dr. S. Meurer of MAN Co. in Germany, burns cleaner, runs quieter, and has unexcelled power output and fuel economy. Furthermore, it can burn with equal ease diesel fuel, kerosene, gasoline, jet fuel and other light and middle distillates. And everything in it is just the opposite of what represented the best practice in diesel engine design only a short time ago.

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ROBERT T. SUTHERLAND, JR.

LITTLE WHEELS, INC.

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an engineering-duty officer prior to his voluntary retirement, is a graduate of the Naval Academy and the Massachusetts Institute of Technology. In the Service, he had wide experience in a variety of assignments, ashore and afloat, at home and abroad, specializing in ship design, construction and maintenance. Subsequent to his retirement, he has discharged duties of various corporate officers in companies engaged in shipping, advertising and manufacturing. Currently, he makes his home in Newtown, Connecticut, where he is a consultant on sales, engineering and management problems.

INTRODUCTION

IN GOOD TIMES, perhaps no business problem is so widely discussed as the ever-increasing need for better executive training and development. An appreciable portion of top management's time and effort are willingly employed in the endeavor to develop a capable management team. Substantial expenditures of corporate funds are made to support promising training programs.

A novel system of training is here proposed, which permits the broad education of large numbers of voluntary trainees of all levels, duly emphasizing the problems and needs of their own business, and which can be undertaken without serious interference with the conduct of that business. Furthermore, by reviewing the record, the system permits management, the candidate, his fellow trainees, superiors and subordinates all to reach the *same* general evaluation of his performance *on-the-job*, relative to the other participants in the program. Incident to the training system, new products, processes and profits may accrue to the sponsoring company, at little or no expense.

ELEMENTS OF AN OPTIMUM SYSTEM

All executive development methods used to date have their limitations. Criticisms range from inconsequential comments to sober statements that this or that program is utterly worthless for company and student. There is vague distrust of "book larnin" and dislike of academic features which, perhaps designedly, do not develop those special skills thought to be important. Some say present programs are too stereotyped and presuppose the same educational background and the same future requirements on the part of all attendants. Fault is found with the scope of available courses and their cost.

Occasional psychological adjustment problems have been encountered in graduates of prescribed courses if promotions were not immediately forthcoming upon completion of formal instruction. They themselves, or others, have believed that they were chosen as "heirs apparent." Serious-minded individuals, anxious to progress, have found it uninteresting to play games with tokens and rehash imaginary or historical cases, preferring to get their teeth into *real* problems, demanding prompt decisions and involving responsibility for those decisions.

Reviewing the deficiencies of present methods, we might agree that any program which met most of the following general requirements would safeguard and further the interests of the company and the individual, and might well be an exemplary training system.

1. The educational program should be useful for all levels of management and should have graduated requirements identifiable with each level.
2. The program should be open to all, on a voluntary participation basis. It should offer equivalent opportunities for personal improvement regardless of formal educational background.
3. The program should be so designed as to facilitate evaluation and appraisal of individual qualifications and attainments.
4. It should involve minimum interference with the conduct of regular business and should be adjustable to meet cyclic, seasonal or peculiar requirements for the full-time services of participants.
5. It should foster knowledge of the participant's own com-

pany and contribute to development of a company point of view.

6. It should be operable at minimum cost to the company and should involve some contribution of time and services by those seeking personal improvement.
7. The extent of an individual's participation should be to a degree dependent upon himself, especially as regards pace of work, specific hours applied and personal contributions.
8. The program should emphasize practical work rather than hypothetical and theoretical problems. There should be a do-it-yourself theme throughout. Demonstrable results should be obtained by effort.
9. By increasing understanding of others' problems, the program should contribute to the development of a spirit of team play.
10. It should lend prestige to the individual participants yet avoid tagging them as "heirs apparent" or promising them promotion as a condition of completing a phase of instruction.
11. Decision-making should be required, for *real* stakes. Full executive responsibility should be incurred for all decisions made.
12. The program should be designed to maintain the interest of all able participants .A competitive spirit, so essential to business under competitive free enterprise, should be encouraged.

WASTE—ANOTHER COMMON PROBLEM

Every business, like every machine, is to a degree inefficient. Gross product output, measured in material units, never equals the theoretically achievable amount obtainable from input. Somewhere along the line, wastes of manpower, materials and money occur. If, under good management, the wastage is kept within tolerable limits and the marketable finished product is competitively priced, the business is likely to continue. But, if waste becomes and remains excessive, the business will almost certainly fail unless management takes prompt and effective measures to reduce waste.

Wasted materials—raw, semi-processed or processed—go up every factory stack and down every drain, out the windows, into furnaces or incinerators, and out of the doors as junk. Some material, thought to have uncertain value, is collected and permitted to gradually fill warehouses, to there gather dust or rust until, urgently requiring space, someone disposes of it at a fraction of its one-time value. Surplus (and therefore wasted) machine capacity and tooling are more or less knowingly overlooked, occasionally in the belief that reductions in the labor and supervisory forces may ensue as a sequel to recognition of idle capacity. Obsolete and inefficient machines and methods are kept in operation in a misguided desire to "let well enough alone," in ignorance of the true state of affairs, in a cover-up of earlier faulty decisions, or perhaps to avoid a paper loss which would follow writing them off the books. Still serviceable but perhaps outmoded tooling, jigs and fixtures, molds and the like, which might be immediately salable to a marginal producer, are stored until they have lost all except junk value.

Wastes of money and manpower in overstaffing, inappropriate usage of overtime, improper purchases, maintenance of unnecessary or obsolete records, inadequate credit investigation, failure to take discounts, unnecessarily rigid specifications, misdirected selling effort, poor decision-making, slipshod traffic handling, inadequate advance planning with its consequent "crash" programs, overlapping of responsibilities and other organizational faults are frequently hidden so long as possible, in fear of management's crackdown on offenders. Many a subordinate knows of the existence of waste, its causes, and the methods of correction.

So long as a business continues to make a minimum return acceptable to its owners, it is convenient for everyone to overlook waste. But, when a business or industry faces extinction because of lower-priced competition, waste becomes the target for every day. Happily, in the absolute necessity of reducing waste in order to stay alive, many a company (and occasionally a whole industry) has changed the nature of its product mix, developing profitable new by-product lines, new processes, new machines, a new spirit and a new lease on life.

Spasmodic attempts are made to handle isolated segments of the waste problem, but generally there is no overall control over the whole problem. No one body is authorized to move into such situations with the responsibility to liquidate or employ those waste assets to the greatest benefit of the company. Yet, a small decrease in wastage, and therefore in cost of the product, is the cheapest and easiest way to substantially increase profits.

SOMETHING FOR NOTHING

To make a double-barreled attack on both the executive development and waste problems, a subsidiary of the corporation might be formed, to be directed, officered and staffed by trainees, charged with the responsibility of making a *profit* on the waste of the present business. The new corporation would serve as a spare-time training ground offering comprehensive experience to candidates experienced in one or few departments of the business. Each trainee would occupy a se'ected position and discharge its responsibilities for a predetermined period, then be reassigned to another position requiring different qualifications, forced out, or permitted to withdraw from the program. The trainee holding the position of Chairman of the Board of Directors of the subsidiary should, for the same period, hold an inside seat on the Board of the parent company, thus facilitating communications between the two.

Each director, officer and management representative of the subsidiary should hold a permanent position in the parent company from which he derives substantially all of his income. His activity in the subsidiary being on a voluntary basis and intended to further his own education and enhance his opportunities in the parent organization, he should receive purely nominal salary in return for his efforts in the subsidiary. His incentive to performance in the subsidiary should be recognition and possible promotion in the parent company, plus perhaps a share of the profits of the subsidiary, determined in pro-

portion to his personal contributions to its success and the responsibilities he has appropriately discharged. Services of a limited number of employees would be obtained by assignment from the parent organization, in response to request from the subsidiary, at a billing rate determined by the parent.

Surplus and waste materials of the parent company should be turned over to the subsidiary for disposal. The subsidiary should be billed at prevailing rates previously collected by the parent for junk, or be paid those prevailing rates paid by the parent for removal of debris from its premises. Warehouse and working space, laboratory and machine shop services, power and other facilities requested by the subsidiary and furnished by the parent, should be billed at agreed-upon rates insuring a profit to the parent.

Services of the subsidiary to the parent, again in response to request, in evaluation of proposals, pilot manufacture, model making, economic and market analyses, or other designated tasks, should be reimbursed by the parent at realistic negotiated rates equivalent to those it would pay other activities for similar satisfactory services.

Proposals of the subsidiary for long-term cost-saving changes in the materials, methods, or other operations of the parent, when supported by adequate analytical studies, should receive serious consideration and, if accepted and applied, should be paid for by an agreed percentage of the savings actually achieved during an initial application period. New products should be paid for on an agreed profit-sharing basis, again for a specified length of time immediately following introduction of the product to the market.

Restrictions should be placed upon the subsidiary as regards working capital, investments allowed, retention of funds, conduct of customer and public relations, types of business which can be engaged in, borrowing and contractual authority. As few limitations as practical should be imposed in order that positions in the subsidiary be truly responsible and that the exercise of good judgment be constantly required.

Directors, officers and supervisors in the subsidiary should clearly understand that they remain fully responsible for their regular assignments in the parent company and that employment in the subsidiary will never excuse malperformance in the parent. While free to delegate their authority in the parent, they personally retain complete responsibility for performance. Attachment to the subsidiary is in all respects "temporary additional duty," volunteered for by the trainee.

All accounting procedures, reports of all kinds, legal responsibilities imposed upon directors and officers, etc., as required of the usual corporation, should be similarly required of the proposed subsidiary in order that the training opportunities be complete in all respects, insofar as practical. Those tentatively selected to first occupy important positions in the proposed subsidiary should be required to handle its organization and establishment subject to the overall guidance and approval of the parent Board of Directors.

FRINGE BENEFITS

Besides meeting most if not all of the conditions earlier set up for an optimum executive training system, the LITTLE WHEELS subsidiary of X Corporation has other important advantages.

The would-be participant in the program who hopes to make a real showing in several successive capacities in the subsidiary must so organize his own department in the parent company, and so train his subordinates, that his having made himself available for additional duties in no sense occasions a reduced performance by his regular department. Furthermore, knowing that any inordinate waste within his regular group is potentially a target of his associates in the subsidiary, he is going to do his best to insure that his own house is in as good order as he and his subordinates can make it.

Since the subsidiary group will be under the watchful eyes of the parent Board and its performance a matter of record which may influence the future opportunities of its members in the parent company, it is logical to expect continuous effort by group members to fully and capably discharge their responsibilities as individuals and as a team. With rotations of memberships as well as positions in the subsidiary, a competitive spirit is engendered, each group attempting to outperform its predecessors. In the process, company-wide recognition of outstanding men is almost certain to develop.

The parent Board of Directors is bound to become better acquainted with the younger executives of the Company if it discharges its duty to supervise subsidiary activities and performance. A favorite complaint of top management is that middle-management and lower-level supervisors are really unfit for promotion because they "lack practical experience." Under this program, likely-looking candidates for promotion to more responsible positions in the parent organization can be eased into the subsidiary for a tryout period. The *useful* positions created by the subsidiary permit on-the-job experience by which the candidate gains *practical* experience in the problems of *general* management.

While no provision has been made for formal instruction as part of these proposals, a lot is going to be learned by a lot of people. Worthwhile individuals put into responsible positions and forced to make their own decisions are almost sure to recognize the limitations placed upon their performance by inadequate knowledge. They will take steps to improve the situation by reading and study, consultation, research and experiment. Learning acquired for a specific purpose will be welcomed, retained and consciously or subconsciously used for other purposes another day.

Any operation of the subsidiary must encourage—

and will in fact require—association between individuals of various levels in all the different departments of the parent company, leading to exchanges of ideas and information, better understanding and appreciation of the other fellow's job and the formation of lasting friendships. The same communication channels developed in the subsidiary will be maintained thereafter to the benefit of the parent corporation.

It is inconceivable that the subsidiary will ever really work itself out of a job by elimination of all waste. As the parent corporation lives and grows, new problems continually arise because of new products, growth itself, aging equipment, material shortages and substitutions, new processes, new applications, etc. The constant influx of new blood into the subsidiary, in the interest of harvesting successive crops of executives, carries with it new ideas, new insights into old problems, recognition of additional wastes, and perhaps younger, fresher and better methods of improving the position of the parent organization.

If and when the subsidiary is thought to have outlived its usefulness, it easily can be dissolved without significant loss and without displacement of key personnel. In fact, the liquidation procedures themselves must further contribute to the education and experience of the final group of trainees.

The U. S. Navy has taken delivery of the largest concrete floating drydock ever built in the United States. Known as "AFDL-48," she is 400 feet in length, 96 feet in overall width, and 68 feet in inside width. The lifting capacity is 4,000 tons. The concrete shell was constructed by General Construction Co., and the drydock was completed by the Seattle Division of Todd Shipyards Corporation.

"SHIPBUILDER AND MARINE ENGINE-BUILDER"

TYPICAL BRITISH WAR VESSELS BUILT DURING THE PAST FIFTY YEARS

ACKNOWLEDGEMENT

This article, written by Lloyd Woollard, a retired member of the Royal Corps of Naval Constructors, was published in the Jubilee Number (July 1956) of "The Shipbuilder and Marine Engine-Builder."

DURING THE PAST fifty years, the occurrence of two major wars and the experience gained in them, together with progress in pure science and general engineering, led to the introduction of new types of warship and rapid developments in existing types. As examples of the former, there may be cited the aircraft-carrier and the modern minesweeper. New developments include the use of guided missiles, the provision of under-water means of detecting submarines, radar and new methods of propulsion. The last-mentioned are still more or less in the experimental stage; the use of hydrogen-peroxide plant in Diesel machinery for submarines, and the application of atomic power to ship propulsion, may be quoted in this connection.

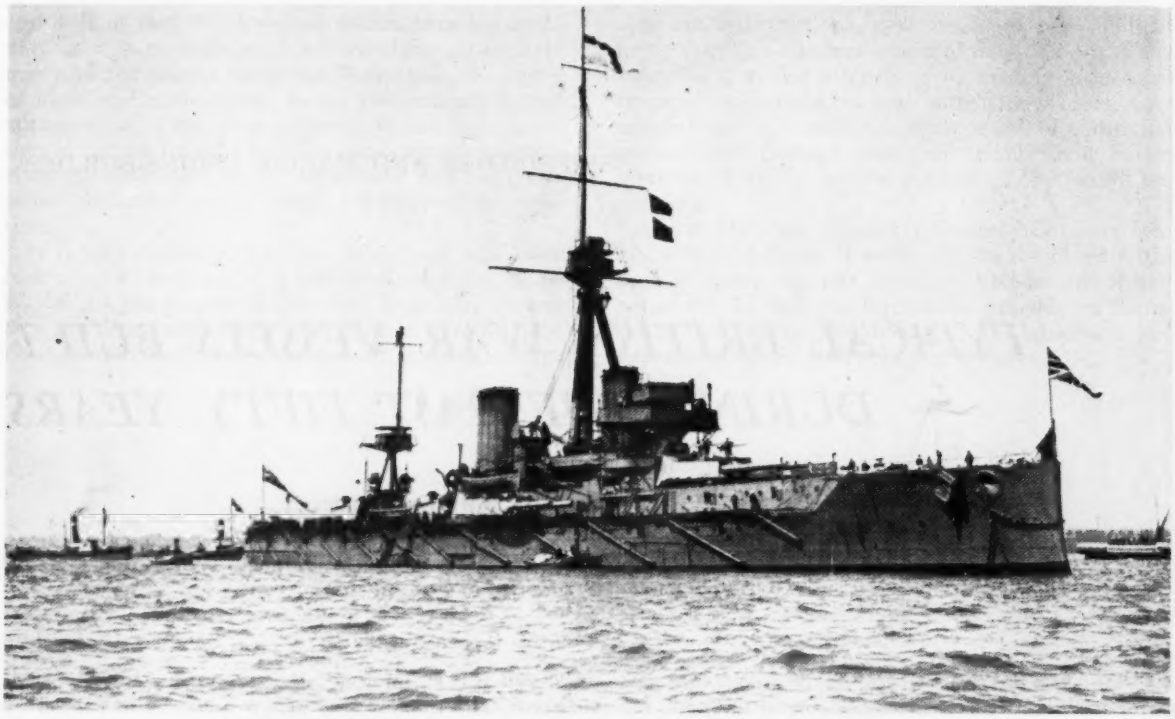
Progress in shipbuilding and marine engineering has been particularly rapid in ships of the Royal Navy, where economy of weight and space are of paramount importance. A brief account of developments in typical naval ships may, therefore, be of interest.

BATTLESHIPS

For some years prior to 1906, battleship designs had followed a fixed pattern. Four 12-in. guns, in two turrets, were mounted forward and aft, along with a broadside battery of 6-in. guns. The ships were driven by steam reciprocating machinery at a speed of 18 knots. In the *King Edward VII.* and *Lord Nelson* classes, some departure from tradition was made, but it was the *Dreadnought*, completed in 1906, which inaugurated a revolution in battleship design. Of a length of 490 ft. 0 in. and a displacement of 18,000 tons, she mounted ten 12-in. guns in five turrets, and was the first large warship to be propelled by steam turbines. These developed 23,000 S.H.P. on four shafts, giving a speed of 21 knots. The thickness of armor belt was increased to 11 in. and higher freeboard forward improved the ship's behavior in a seaway. Ships of similar design to the *Dreadnought* followed year by year, until the *Orion*-class ships were laid down in 1910, when ten 13.5-in. guns were mounted, all on the center-line, the ship's length and displacement becoming 545 ft. 0 in. and 22,500 tons.

The *King George V.* and *Iron Duke* classes followed on similar lines, but in the five ships of the *Queen Elizabeth class* (completed during the war), the main armament was increased in caliber and became eight 15-in. guns. Fuel oil was exclusively used, and the belt thickness raised to 13 in. Special attention was paid to defense against torpedoes, close watertight subdivision and an under-water protective bulkhead being provided. The ships were 600 ft. 0 in. in length, had a standard displacement of 31,000 tons, and were propelled by turbines of 75,000 S.H.P., giving the unprecedented speed of 25 knots. The ships of the *Royal Sovereign* class which followed were slightly smaller and slower. As a result of war experience, some of these ships were later modernized. Among other improvements, their under-water protection was strengthened by fitting "bulges" at the ship's sides, and the deck protection raised to 2½ in.-4 in.; increase in displacement was obviated or reduced by installing new and much lighter main machinery of the same power.

The next battleships to be completed were the *Nelson* and *Rodney*, in 1927. The displacement was rigidly limited to the Washington Treaty figure (35,000 tons), so that their design called for most accurate and careful estimation of weights. Their



H.M.S. "Dreadnought"—Battleship which Revolutionized Naval Warfare.

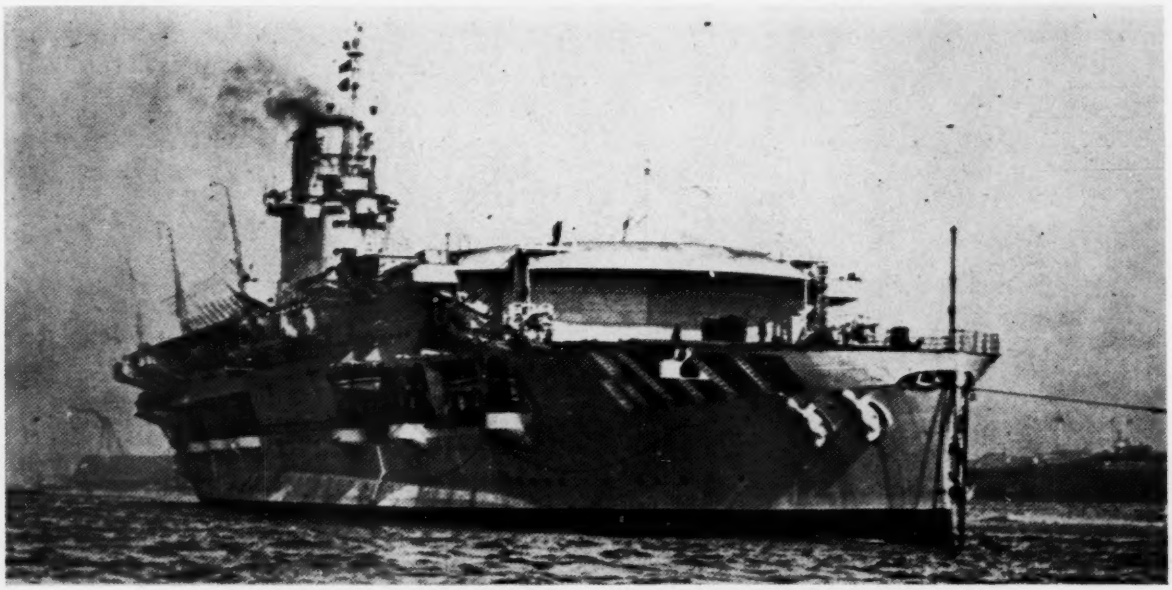
dimensions were 710 ft. 0 in. by 106 ft. 0 in. by 30 ft. 0 in. (mean draft), and the single-reduction geared turbines, on two shafts, developed 45,000 S.H.P., giving a speed of 23 knots. These ships were noteworthy for their concentrated "citadel," all main armament (nine 16-in. guns in three turrets) being situated, together with the magazines, forward of the bridge, which reduced to a minimum the weight of the surrounding protection. The side and barbette armor were, respectively, 14 in. and 15 in.; to provide protection against long-range fire and air bombing, the deck over the machinery and magazines was made 6¼ in. thick.

Until 1937, no more capital ships were built, but the five ships of the new *King George V.* class were laid down. Their standard displacement was again limited, by Treaty, to 35,000 tons, and their dimensions are 745 ft. 0 in. by 103 ft. 0 in. They are armed with ten 14-in. guns in three turrets (two of them quadruple) and lighter armament, and are heavily protected on deck and sides, the belt thickness being 16 in. With 112,000 S.H.P. on four shafts, their speed is 28 knots.

The *Vanguard*—the latest, largest and most powerful British warship, and perhaps the last battleship to be built—has dimensions of 815 ft. 0 in. (overall) by 108 ft. 0 in. by 28 ft. 0 in., with a standard displacement of 44,500 tons. Machinery on four shafts, developing 130,000 S.H.P., gives a sea speed of 29½ knots. She is armed with eight 15-in. guns in four turrets, sixteen 5¼-in. guns and A.A. armament, with fire-control and radar embodying the most modern scientific devices. Damage control, also, is elaborate, and the engine and boiler-rooms are in four self-contained units. Accommodation of improved type is provided, together with such amenities as laundry, movies, chapel, and excellent ventilation and air-conditioning arrangements. The two stream-lined funnels, with sloped caps, give an up-to-date appearance, while the good freeboard, flare forward and triple breakwater ensure a dry ship.

BATTLE-CRUISERS

The earliest warships of this type—three ships of the *Invincible* class—were laid down in 1906. They may be regarded as a continuation of the armored cruisers of the *Minotaur* class, but they have the characteristics of a fast battleship, in which some protection has been sacrificed to gain speed. Their inception, like that of the *Dreadnoughts*, was due to Lord Fisher. The *Invincible* had dimensions of 530 ft. 0 in. by 78 ft. 6 in., with a displacement of 17,250 tons, and was propelled at 25 knots by turbine machinery of 41,000 S.H.P. Eight 12-in. guns were mounted in four turrets; side protection was given by a 6-in. belt. These vessels were succeeded by three similar ships of the *Indefatigable* class, and then by the larger *Lion, Princess Royal* and *Queen Mary*, with dimensions of 660 ft. 0 in. by 88 ft. 6 in., and a displacement of 26,300 tons. The horse-power was raised to 70,000, the speed to 28 knots, and the belt armor to 9 in. The final ship of this series was the *Tiger*, of 28,500 tons, with eight 13½-in. guns;

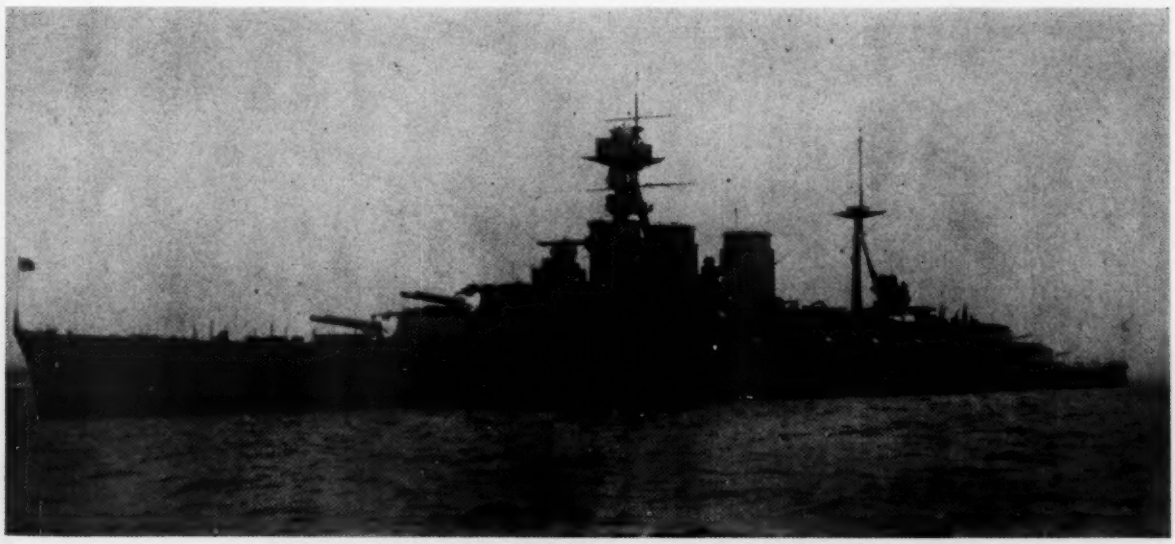


H.M. Aircraft-carrier "Courageous," after Conversion from Light Battle-cruiser.

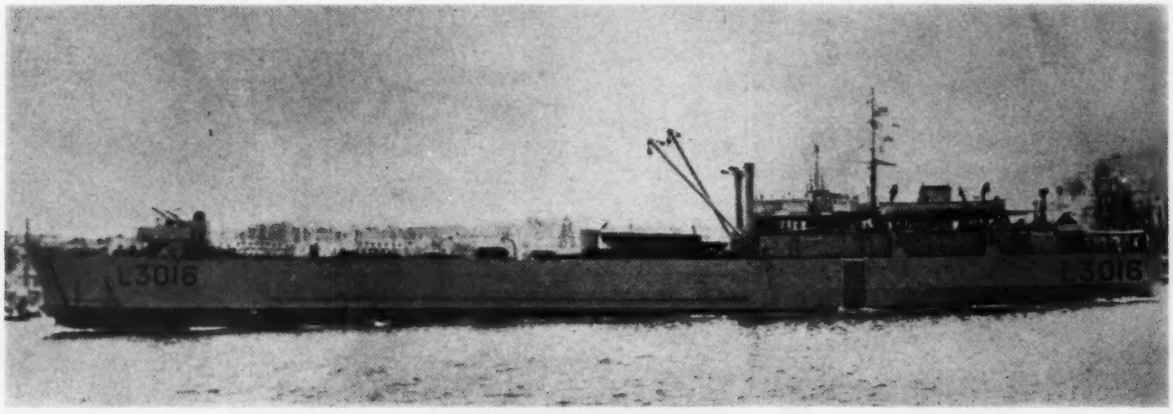
she was oil-burning, and propelled at 30 knots by machinery of 108,000 S.H.P.

In 1915, two lightly-protected but heavily-armed and fast ships were laid down, one of which (*Renown*) survived until recently. With dimensions of 750 ft. 0 in. by 90 ft. 0 in. by 25 ft. 6 in., and displacing 26,500 tons, she mounted six 15-in. guns, and attained a speed of 32 knots with machinery of 112,000 S.H.P. This ship was designed with bulge protection; later, she was twice modernized, being given a 9-in. belt (in place of 6-in.), larger bulges, improved watertight subdivision, and new machinery. The *Renown* was several times employed on overseas Royal tours.

The ships of the *Courageous* class, designed as "light cruisers carrying heavy guns," were eventually converted to aircraft-carriers, and are described as such below. The *Hood*, a heavy battle-cruiser and the last ship of that type to be built, was laid down in 1916. The dimensions were 810 ft. 0 in. by 104 ft. by 28 ft. 6 in., displacement of 41,200 tons, S.H.P. 144,000, and speed 31 knots (32 knots on trials). Armed with eight 15-in. and ten 5½-in. guns, she also carried six 21-in. torpedo-tubes, four of which were above water. The ship was bulged, and protected by 12 in.-5 in. side armor, and 2-in. p'ating on deck; the belt protection was increased after the Jutland action, and 5,000 tons added to the displacement.



H.M. Heavy Battle-cruiser "Hood"—Last Ship of the Type to be Built.



H.M. Tank-landing Ship "Dieppe."

AIRCRAFT CARRIERS

This type of warship—a comparatively new creation, in which Great Britain can fairly claim to have been a pioneer—had as forerunners a few mercantile ships converted and adapted to carry seaplanes, which were lifted on board or lowered by a derrick.

The first ship designed and built to land and fly-off aircraft was the earlier *Hermes,* completed in 1924, which displaced 10,800 tons and had a speed of 25 knots. Progress in aircraft demanded a small fleet of carriers, and this was met at the time by converting a number of warships, of which the most important and useful were the "light" battle-cruisers *Furious, Courageous* and *Glorious.* A large superstructure was built, providing space for hangars; two aircraft elevators were installed, and enlarged sleeping and messing spaces arranged to accommodate the greatly increased complement.

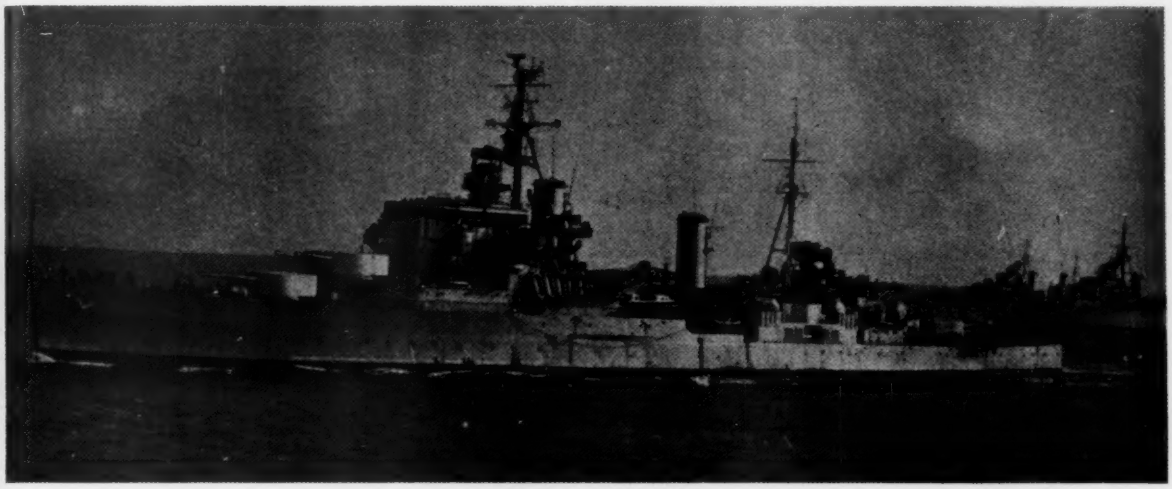
A feature of these carriers (except for *Furious*) and of all subsequent carriers was the island built on the starboard side of the superstructure. This incorporated the funnel, mast and positions for navigation and control, leaving the remainder of the flight deck free and unencumbered except for the arresting devices required when planes were landing. Stability was safeguarded by enlarging the ship's bulges, thus countering the effect of the topweight added.

Particulars of the *Courageous* after conversion were: Length, 786 ft. 0 in.; displacement, 22,500 tons; speed, 30½ knots, with 90,000 S.H.P.; armament, sixteen 4.7-in. guns; accommodation for about 50 airplanes.

The three ships *Furious, Courageous* and *Glorious* were very fine aircraft-carriers, and we'l in advance of any previously built or then being built at home or abroad. There has been much progress in carrier design since, particularly in the direction of belt and deck protection, an angled flight deck, the installation of catapults, and improved equipment all round. The succeeding classes are as follows:

Illustrious class, laid down in 1937, with dimen-

H.M.S. "Latona"—Typical War-time Destroyer (40 knots), Bombed and sunk at Tobruk



H.M. Cruiser "Superb."

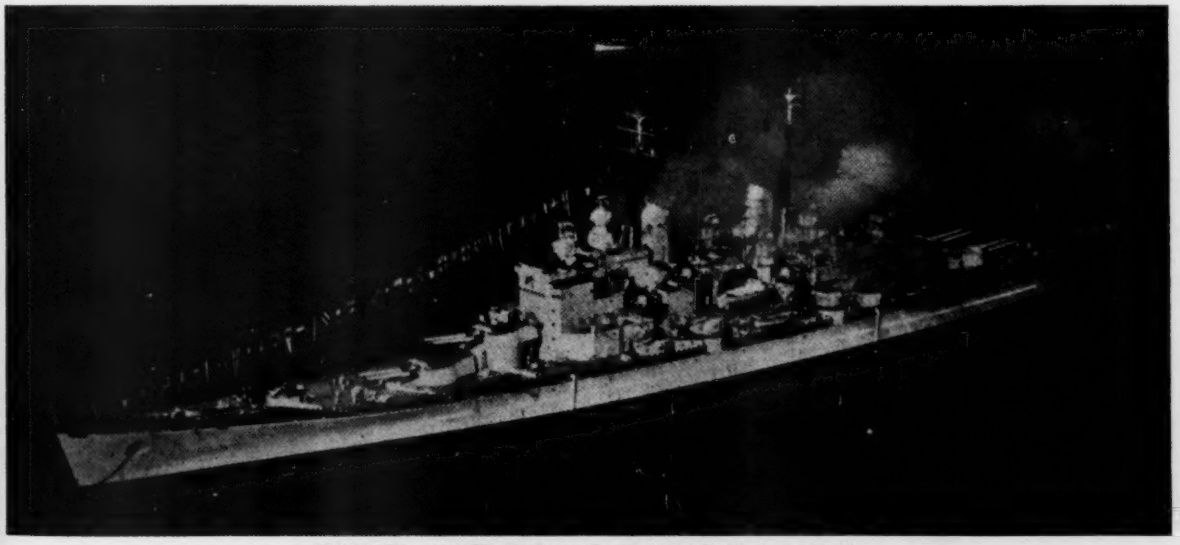
sions 753 ft. 0 in. by 95 ft. 0 in.; displacement about 23,000 tons; machinery (turbines on three shafts), 110,000 S.H.P.; speed, 31 knots. She is armed with sixteen 4.5-in. and lighter guns, and protected with a 4½-in. belt and 3-in. to 2½-in. on decks; 60 aircraft are accommodated. The *Indomitable* followed, slightly larger, and after the war was modernized. The *Victorious* (of *Illustrious* class) is being modernized and given an angled deck.

In 1939, the *Implacable* and *Indefatigable*, each of 23,000 tons, were commenced and were followed by lighter ships, *viz.* (in 1942), the *Colossus* class, 695 ft. 0 in. by 80 ft. 0 in., displacing 13,350 tons, with machinery of 40,000 S.H.P. on two shafts, and speed of 25 knots. These ships carry 35 aircraft, and are prepared for tropical service and air-conditioned. These were followed (1943) by the *Majestic*, generally similar.

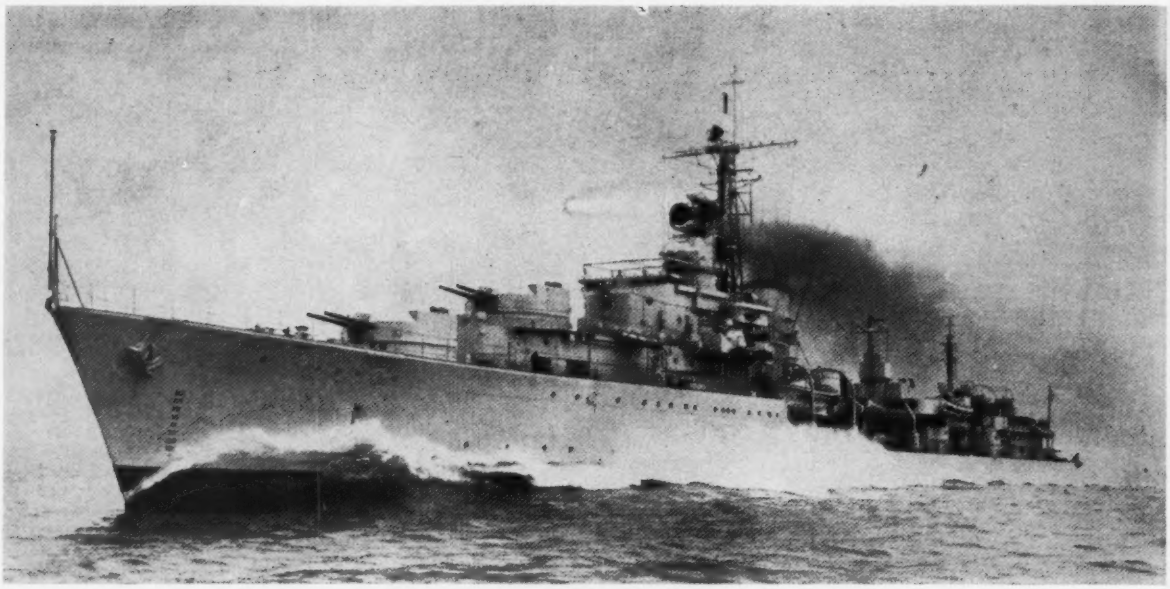
Post-war carriers include the *Hermes* class, of 20,000 tons and 28 knots speed, and, finally, the *Ark Royal* and *Eagle*. The last-mentioned two ships are the largest aircraft-carriers in the Royal Navy, having dimensions 808 ft. 0 in. by 112 ft. 0 in., and displacement of 36,800 tons standard and 46,000 tons deep. The armament is sixteen 4.5-in. and anti-aircraft guns; they accommodate 80 to 110 aircraft. The ships are propelled by turbines of 152,000 S.H.P. on four shafts, with a speed of 31½ knots. These ships embody all features and equipment found necessary for operating the largest and most modern aircraft. In the *Ark Royal*, these include a deck-edge elevator amidships (making three elevators in all) and steam catapults. Minor landing sights are also incorporated.

CRUISERS

As already mentioned, the armored cruisers built or being built before 1906 were replaced by battle-cruisers; the small unarmored cruisers then under



H.M.S. "Vanguard"—Perhaps the Last Battleship to be Built.

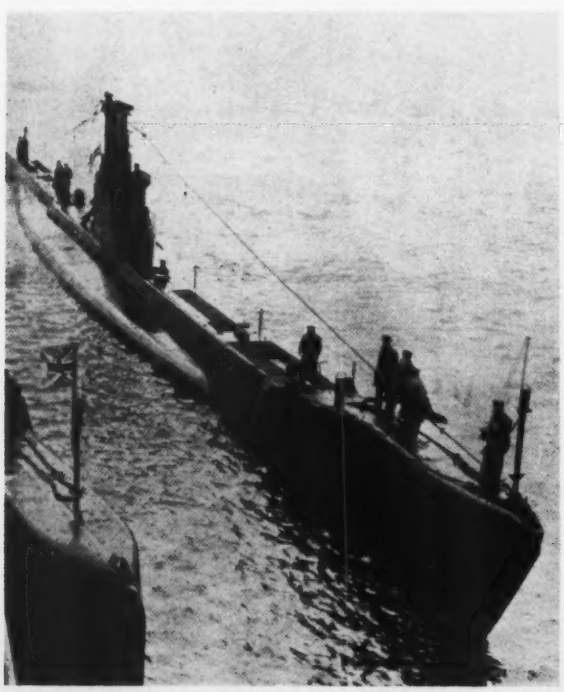


H.M. Destroyer Flotilla-leader "Agincourt."

construction may be regarded as the successors of the light cruiser *Boadicea* (1908), of 3,400 tons, with 26 knots speed and armed with 4-in. guns. She was succeeded by several classes, having sightly greater dimensions, of which the *Weymouth* (1910) may be cited. With a length of 430 ft. 0 in. and 5,250 tons displacement, she mounted eight 6-in. guns, and was propelled by turbine machinery on four shafts developing 22,000 S.H.P. at 25 knots.

Following, was the *Arethusa* class, built in 1912 to 1914, with 2½-in. belt protection and 29 knots speed; the machinery of 40,000 S.H.P. ran on fuel oil.

These were succeeded by the "C" and "D"-class cruisers, which were built in large numbers and constituted an important part of the small cruiser strength at the outbreak of the Second World War. "D" cruisers were 445 ft. 0 in. long and displaced



H.M. Submarine "Acheron" Returns to her Depot Ship, H.M.S. "Adamant," in Rothesay Bay.

H.M. Destroyer "Daring."

H.M. Fast Patrol-boat "Gay Bombardier," fitted as a Motor Torpedo-boat.

4,650 tons; their speed was 29 knots, and S.H.P. 40,000. They were armed with six 6-in. guns and protected by a 3-in. belt. A few larger cruisers were built or commenced during the First World War; they were the *Frobisher* class, of nearly 10,000 tons and armed with 7.5-in. guns, and *Emerald,* of 7,550 tons and mounting seven 6-in. guns.

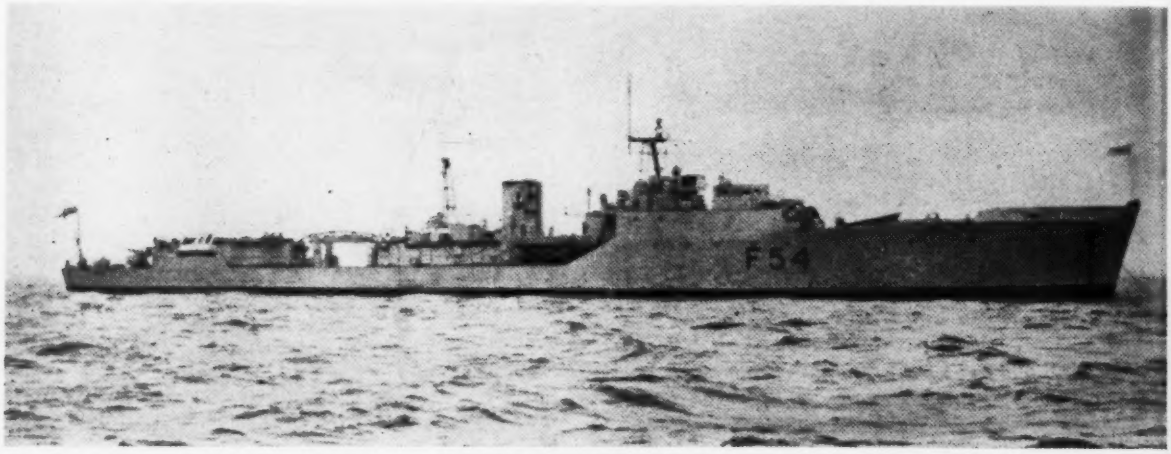
Between the wars, the Washington Treaty (1922) and the two London Treaties (1930 and 1936) exercised a considerable influence on the design of warships. The Washington Treaty limited the standard displacement of cruisers and lesser war vessels to 10,000 tons. The 1930 Treaty divided cruisers into two categories—those armed with guns not exceeding 6.1-in. caliber, and those mounting heavier guns; the total tonnage of each category was limited to a definite figure. The 1936 Treaty limited future cruisers to a standard displacement of 8,000 tons and their armament to 6.1-in. or less, but without total tonnage limitation.

The first cruisers built after the First World War were the *Kent* class, armed with 8-in. guns (then allowed by the Washington Treaty), which is the heaviest armament mounted in any cruisers of the Royal Navy before or since. All of these, with the exception of two ships, attained approximately the 10,000-ton limit permitted for displacement, and were armed with eight 8-in. guns in four turrets. They were propelled by turbine machinery developing 80,000 S.H.P., and attained a speed approximating 32 knots, which has become an almost standard cruiser speed since.

The *Kent* class were first built (1924-28) with dimensions of 630 ft. 0 in. by 68 ft. 6 in. by 16 ft. 6 in.; "box" protection was provided around and over the magazines, and an underwater bulge at the sides gave some immunity against torpedo attack. The ships also carried eight 4-in. anti-aircraft (A.A.) guns and eight 21-in. torpedo-tubes (quadruple). It is noteworthy that one ship (*Cumberland*) of the class still survives and is used as an experimental ship for various trials, including those of new weapons and defense against them. She has been fitted with anti-rolling stabilizers.

The *London* and *Dorsetshire* classes followed, generally resembling the *Kent,* but the latter's external bulge was replaced by internal anti-torpedo protection. The dimensions were 633 ft. 0 in. by 66 ft. 0 in. by 17 ft. 0 in., and the slight change in the lines raised the speed from 31½ to 32 knots. The actual displacement of these vessels was somewhat less than the 10,000-ton Treaty limit, and this margin enabled the cruisers to be later reconstructed and modernized. An armor belt was added, and the four 4-in. A.A. guns were replaced by eight in twin mountings. A catapult and two aircraft hangars were also added. The two remaining ships with 8-in. guns were the *York* and *Exeter,* displacing about 8,000 tons. Only six 8-in. guns were mounted in them, and a 3-in. belt was provided, together with magazine protection. The calculated stresses for these long cruisers in a seaway were very high, and probably greater than would arise in other types of ships. Steel of special quality was used, and the structural design carefully adapted to enable all stresses to be safely borne.

A reversion to 6-in. armament was made in 1930 with the *Leander* class, and these were followed by



H.M. Frigate "Hardy."

the *Arethusa* class, having dimensions 500 ft. 0 in. by 52 ft. 0 in.; displacement, 5,200 tons; armament, six 6-in. and eight 4-in. A.A. guns; 64,000 S.H.P. and 32½ knots speed. They were followed by the larger and important class of cruisers of the *Southampton* and later classes. These ships were 590 ft. 0 in. by 62 ft. 0 in. by 17 ft. 0 in. and had a standard displacement of 9,100 tons; armament—twelve 6-in., guns in triple mountings and eight 4-in. A.A. guns, with six 21-in. torpedo-tubes. In the later ships (*Belfast*), with 10,000 tons displacement, improved magazine protection was introduced. Her speed was 32 knots. The *Belfast* has since been modernized and her displacement increased to 11,500 tons; she is now the largest cruiser in the Royal Navy.

The cruisers built or completed during the war comprise the *Dido* class, similar to the *Arethusa* in dimensions, but mounting ten 5¼-in. guns and being given 2-in. side protection. Also the *Ceylon* class, *Superb* and *Swiftsure*, which resemble in size and armament the *Southampton* class, but have a 4-in. belt and improved fire control. In the *Southampton* class and later ships, one triple 6-in. turret was removed during the war, to increase the light A.A. armament. The *Tiger* class, of about the same dimensions are still under construction.

DESTROYERS

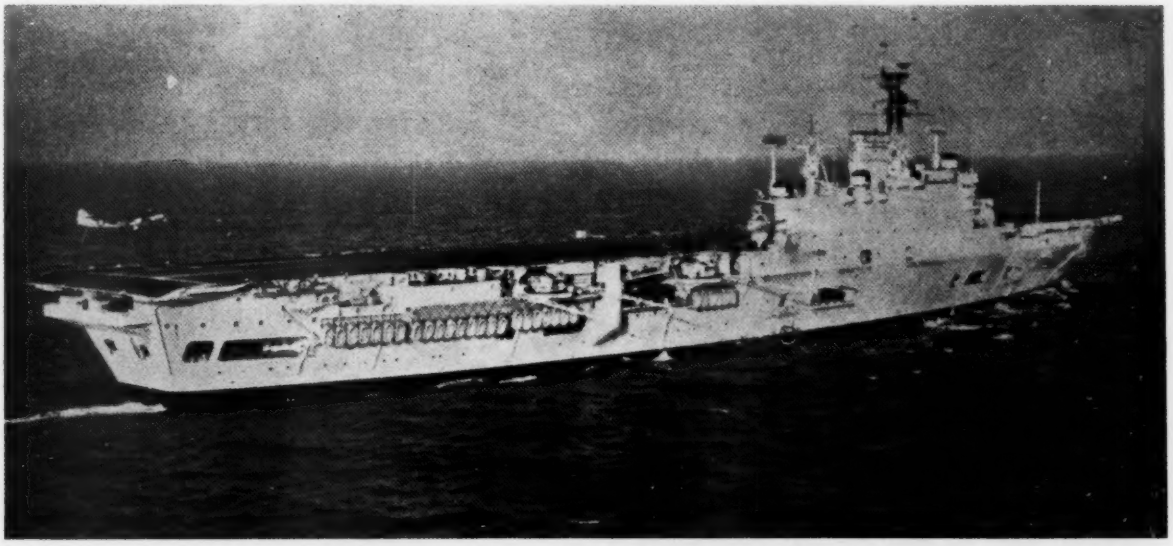
The number of destroyers available in 1939, at the beginning of the last war, was about 160, in addition to 18 flotilla-leaders. A comparable number have been added to the Fleet since. Instead of attempting any account of the ships, class by class, it is therefore convenient to indicate the general trend of their development.

The characteristics of a destroyer are high speed (generally from 30 to 36 knots), light hull and machinery (the latter very powerful), a gun armament equivalent to that of a small cruiser, and a torpedo armament up to ten 21-in. tubes, the number depending on the nature of the service. The speed of a destroyer, *relative to her size*, is greater than in any other normal ship, and her lines and proportions are made specially suitable for the attainment of this abnormal speed.

Many destroyers are adapted for special services, such as anti-aircraft, anti-submarine and minelaying; and in the first two capacities, the ships are suitable as escorts to either large warships or merchant convoys. As with cruisers, their light scantlings lead to high structural stresses in a seaway; in the "J" class (1937) and all later classes, the longitudinal framing adopted has led to somewhat lower stresses, *i.e.*, to higher factors of safety.

From 1906 until the end of the First World War, British destroyers did not vary greatly in dimensions, having lengths of between 250 ft. 0 in. and 300 ft. 0 in., and displacements of between 900 and 1,100 tons. A few flotilla-leaders had displacements of about 1,500 tons. The main armament was two or three 4-in. guns and up to four 21-in. torpedo-tubes. The S.H.P. of the machinery varied from 12,000 to 27,000 (in the later ships), with 27 to 36 knots.

After the war, there was an intermission of some years, but, about 1927, destroyer building recommenced. For some years, the ships were slightly larger, about 300 ft. 0 in. long, with 1,300 tons displacement; but, in general, of much the same type as before. In 1936, however, a demand arose for fast well-armed ships to counter those being built for other navies. As a result, the 16 ships of the *Tribal* (or *Afridi*) class were laid down, with dimensions of 365 ft. 0 in. by 37 ft. 0 in.; displacement, 1,870 tons; S.H.P., 44,000; speed, 32½ to 36 knots (depending on load). The ships were armed with eight 4.7-in. guns in twin mountings, four torpedo-tubes and 30 depth charges. They were followed by the "J" class, laid down in 1937, which were slightly smaller (displacement, 1,760 tons), the power and speed being about the same. The main armament was increased to six 4.7-in. guns, 10 torpedo-tubes in quintuple mountings and 30 depth charges.



A Seahawk Landing on H.M. Aircraft-carrier "Ark Royal."

Early in the war appeared the smaller *Hunt* class, built for escort work, but now converted into anti-aircraft frigates. The dimensions varied from 272 ft. 0 in. by 29 ft. 0 in. to 280 ft. 0 in. by 31 ft. 6 in.; displacement, 1,000 to 1,050 tons; S.H.P., 19,000 with speed 27 to 27½ knots. The main armament consisted of from four to six 4-in. and A.A. guns; generally, there were no torpedo-tubes, but the later ships carried two. The modified *Hunt* ships, with 1,300 tons displacement, carried six 4-in. guns and three torpedo-tubes.

The *Milne* class, of more normal dimensions (354 ft. 0 in. by 37 ft. 0 in., 1,920 tons, 48,000 S.H.P., 36 knots), were the first destroyers to be equipped with the more powerful armament of six 4.7-in. and one 4-in. guns, with four to eight 21-in. torpedo-tubes.

A large number of other war-built ships were given a displacement of about 1,710 tons, and were armed with four 4.7-in. guns and eight torpedo-tubes. Most have now been converted into fast anti-submarine frigates, but the "C" class, armed with 4.5-in. guns, have remained anti-submarine and minelaying destroyers.

Later destroyers are the *Battle*, *Weapon* and *Daring* classes, the last being 390 ft. 0 in. by 43 ft. 0 in., with a standard displacement of 2,610 tons, and the *Battle* class slightly smaller. The *Weapon* class, of 1,980 tons, act as anti-submarine escorts and are armed with four 4-in. guns, two squids, as well as ten 21-in. torpedo-tubes.

The *Daring* class are propelled on two shafts by double-reduction geared turbines of modern type, designed by Pametrada and developing 54,000 S.H.P. The speed is 34¾ knots. They are armed with six 4.5-in. guns in twin turrets and six 40-mm. A.A. guns (all radar controlled), also ten 21-in. torpedo-tubes and squid. These ships are most completely equipped for all the duties that can be undertaken by destroyers, both anti-aircraft and anti-submarine; they embody all modern improvements that experience in the late war has suggested. This applies, also, to accommodation and amenities in general.

SUBMARINES

Early submarines built before the "D" class were propelled on the surface by gasoline engines, and, in other respects, differed markedly from the "D" and subsequent classes. The "D" class (1907-1910) were propelled by twin-screw Diesel engines, the ships being 162 ft. 0 in. in length and having external ballast tanks; their displacement, horsepower and speed were, respectively, 500 (620) tons, 1,200 (500) and 14½ to 15 (10) knots, the data in parenthesis referring to the submerged condition. These vessels carried three torpedo-tubes, and *D.4* was the first submarine to be armed with a gun (a 12-pounder).

Two of the remaining submarine classes built during the First World War were still in use when the Second World War began in 1939, *viz.*, the "H" and "L" classes. Of these, the "H" class was of special interest, for it was the type in use for training in submarine duties. These vessels were smaller than most contemporary classes, their particulars being—Length, 164 ft. 0 in.; displacement, power and speed, respectively, 440 (500) tons, 480 (320) and 13 (10½) knots; they were armed with four 21-in. torpedo-tubes.

The remaining submarines which survived until 1939 were the six minelayers of the *Porpoise* class (displacement 1,520 tons), the larger submarines of the *River* class (1,850 tons), the "O," "P" and "R" classes (1,475 tons) and the "S," "T" and "U" classes. The last three formed the basis of most of the submarines used in the 1939 war.

The accompanying table, which has been extracted by permission, from the paper on "British Sub-

H.M. Light Fleet Aircraft-carrier "Albion" and H.M. Desroyer Flotilla-leader "Cossack" Refueling from the R.F.A. Oiler "Wave Master."

H.M. Yacht/Hospital Ship "Britannia."

"S," "T," "U," "A" and "XE" (Midget) Submarines

Class	"S."	"T."	"U."	"A."	"XE" (Midget).
Length overall	217ft.-0in.	273ft.-5in.	196ft.-10in.	281ft.-8in.	53ft.-2in.
Breadth extreme	23ft.-9in.	26ft.-7in.	16ft.-1in.	22ft.-3in.	5ft.-9in.
Displacement (tons)—					
Standard	715	1,090	545	1,120	—
Surface	814	1,321	658	1,385	30.3
Submerged	990	1,571	740	1,620	33.6
Fuel oil (normal, tons)	44	132	55	159	—
Surface S.H.P.	1,900	2,500	615*	4,300	42
Maximum surface speed (knots)	14¾	15¼	11¼	19	6½
Submerged S.H.P.	1,300	1,450	825	1,250	30
Maximum submerged speed (knots)	9	9	9	8	6
Torpedo tubes	6 bow 1 external	6 bow 5 external	4 bow	6 internal 4 external	— —
Torpedoes carried	13	17	8	20	—
Guns	One 3-in. One Oerlikon Three Vickers G.O.	One 4-in. One Oerlikon Three Vickers G.O.	One 3-in. Three Vickers G.O.	One 4-in. One Oerlikon Three Vickers G.O.	— —
Crew	48	61	33	61	4

*"U" class had Diesel-electric drive; the remainder, direct drive.

marine Design During the War (1939-45)," by Mr. A. J. Sims, and included in the Transactions of the Institution of Naval Architects for 1947, gives particulars of these classes and of two others designed during the war.

The "S"-class ships were designed for offensive patrols in confined waters, and were found very successful for North Sea work. Their construction was continued throughout the war, the last ships being completely welded, with appreciable saving in weight and improvement in robustness of hull structure. The "U" class, in succession to the "H" class, were used for training and for short-distance patrols. They were thus suitable for work in the Mediterranean, where their limited endurance was acceptable. The "T" class were replacements for, and improvements on, the "O," "P" and "R" classes. A number of them were all-welded, which, apart from other benefits, enabled some of the main ballast tanks to be converted into fuel-oil tanks, without fear of leakage through rivets. The endurance of these vessels, already high, was thereby further raised, so that they were rendered very suitable for work in the Far East.

The "A"-class ships, designed during the war, and thus benefiting by war experience, were given higher surface speed and more endurance, and the structural design was improved by being, from the beginning, arranged for welding instead of being adapted. The slightly larger size of the ships also enable habitability to be improved and certain up-to-date design and scientific features to be incorporated. Air conditioning was embodied in the ventilation and accommodation rearranged. In short, the "A" class are very fine ships, suitable for service in the Far East or any other part of the globe.

The "XE" class is a midget submarine, based on the earlier and slightly smaller "X" class, which had been successfully operated in the war. Twelve "XE" submarines were built and found suitable, by experience, for Far Eastern operations. Experimental submarines are now under construction, using novel methods of propulsion; little information about them, however, has been released.

Two important improvements have been made in many of the later existing submarines. The first is the addition of a "Snort" mast—a hollow tube through which air may be supplied to a submarine when the mast is raised and the vessel submerged, though not below periscope level. The Diesel engines may then be used for slow running even when submerged. Secondly, small escape chambers have been built in submarines, which, in event of a disaster, the crew may enter, flood and thence escape to the sea surface, either wearing the Davis apparatus or (after training) following the practice of "free escape."

MISCELLANEOUS

The variety of naval vessels now constituting the Fleet is very great, and it is possible, here, only to touch on the remaining types. Of these, the minesweeper has become important since the beginning of the First World War, when the laying of moored mines in the shallow North Sea and Estuaries around the British Coast constituted, at first, a serious menace. This was met by rapidly building a large number of minesweepers in small yards throughout the country and using them, together with converted trawlers, for sweeping. Today, the *Ocean* minesweepers of about 1,000 tons, together with coastal ships of 350 tons and motor minesweepers down to

100 tons, are available. In the Second World War, the magnetic mine appeared and was countered by "degaussing," which neutralized the ships' permanent magnetism and rendered the mine ineffective; other types of mine, including the acoustic variety, have been used and appropriate counter-measures introduced.

The frigate is another useful type of small ship, used for patrol and escort duties and capable of meeting submarine or aircraft attack. These vessels, have, on the average, 1,500 tons displacement and a speed of about 20 knots. A large number were designed, built and used during the recent war, and many special types are now being built.

Oiling at sea has been developed and, in some degree, perfected; for this purpose, oilers for supplying H.M. ships, as well as naval tankers, have been built in number. The latest oilers include the *Wave* class of about 12,000 tons deadweight, and turbine-driven at 15 knots.

Combined operations have given rise to the design and production of landing ships, tanks and barges. These are required to land, on a hostile beach, men or vehicles, or stores. A typical landing ship is 345 ft. 0 in. by 54 ft. 0 in., displacing 2,250 tons, and propelled at 13 knots by twin-screw reciprocating engines of 5,500 I.H.P. They carry 18 tanks, 35 other vehicles, 260 officers and men (including crew). Their loaded draft at the bow is only 4 ft. 0 in., so as to facilitate beaching; the stern, also, was strengthened by fitting a special skeg. Landing craft are much smaller vessels, frequently shaped like miniature floating docks, and of great diversity; no fewer than 60 types or "marks" have been constructed. They were used for carrying infantry, tanks and other loads.

Among the smaller craft must be mentioned the motor launches, particularly those of the Fairmile type, many of which were prefabricated from plywood by sawmill owners or furniture makers near London, and assembled at the sea by yacht-builders. Fast, motor torpedo-boats, together with motor and steam gunboats, were also built as a counter to the German "E"-boat.

Patrol boats, depot and repair ships, salvage ships, cable ships and others can only be mentioned here; but one ship may be referred to in more detail, *viz.*, H.M. Yacht *Britannia*, which is designed to function also as a naval hospital ship.

Before the present time, the only permanent naval hospital ship was the *Maine*. This vessel was converted and, in many ways, was unsatisfactory and out-of-date. The construction of the *Britannia* has at length enabled the Navy to have, at reasonably short notice (when required), a hospital ship that can accommodate 200 patients, complete with special wards for zymotic and tuberculosis patients, and operating theater, and all necessary accommodation. Anti-rolling stabilizers, air-conditioning plant and extensive laundry facilities are provided. The Royal Yacht has been described elsewhere, and it may suffice to repeat that her dimensions are 360 ft. 0 in. by 54 ft. 6 in.; displacement, 5,770 tons; S.H.P., 12,000; and continuous speed, 21 knots. The ship is suitable for both tropical and Arctic conditions, and, in appearance, habitability and general efficiency, well worthy of the important function she fulfills.

A new type of nuclear reactor designed and to be built by Atomics International, a division of North American Aviation, Inc., has been selected by American and Foreign Power Co., Inc., for installation in a Latin American country. The reactor, called the OMR (Organic Moderated Reactor) will produce 10,400 kilowatts of electricity.

H. J. STARK and M. GLICKMAN

ADHESIVE BONDING OF POLYSTYRENE FOAM FOR NAVAL SERVICE

THE AUTHOR

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Mr. M. Glickman received his technical training at the Philadelphia College of Pharmacy and Sciences before and after Word War II. During the war he flew as a member of the Eighth Air Force and was awarded the D.F.C. In 1950 he joined the staff of the Industrial Test Laboratory of the Philadelphia Naval Shipyard and worked in the metals section. In 1952 he became a member of the impregnated fabrics group of the research and development section. His work dealt primarily with synthetic fabrics. In 1953 he became a member of the foamed plastics group of the research and development section and currently is supervisor of the group. In 1956 he received a B.Sc. degree in Industrial Management from LaSalle College. He is a member of the Industrial Test Laboratory Technical Supervisors Association.

INTRODUCTION

EXPANDED POLYSTYRENE is a light weight, high strength, water resistant, rot resistant, unicellular plastic. Its multitude of small cells are sealed off from each other thus providing it a high degree of buoyancy when placed in water. More detailed information concerning its properties may be found in reference 1.

Cellular polystyrene is used to a very large extent by the Bureau of Ships, Navy Department and most of the small boat industry to provide sufficient buoyancy to these craft to render them unsinkable in the event they become swamped in heavy seas or otherwise become flooded.

The selection of a suitable adhesive for this purpose at first appears to be a simple task inasmuch as the shear strength of the product itself is comparatively low. The manufacturer of the product furnishes considerable information concerning many different types of adhesive and mastic compounds that may be used for bonding expanded styrene. (See reference 2.)

Many of the Bureau of Ships uses for this product would be in wood and plastic boats. It was desirable to use adhesive or mastic compounds that are usually available in Shipyards or from Standard Navy stocks.

It became apparent that the specific selection of suitable adhesives that would withstand rigorous

naval service was not a simple matter. The use of common materials such as linoleum cements, or certain of the materials from a long list suggested by the manufacturer of the foam product (reference 2) left many questions pertaining to strength and durability unanswered. This evaluation program therefore, was designed to test and compare the result of tests on the materials described herein. This would then permit the selection of those materials for naval service which were most acceptable on the basis of these tests.

MATERIALS

The polystyrene foam is hereinafter referred to as "STYROFOAM" which is the trade mark owned by the Dow Chemical Co. and its use here is not intended to detract from the copyright or trademark. Number 22 STYROFOAM is white in color and has no fire retardant properties. Number 33 STYROFOAM is blue in color and has fire retardant properties. Both of these products are described in references (1) and (3). They are both used in this investigation .

The wood product used was Douglas fir plywood (½ inch, five ply, exterior grade) obtained from standard Navy stock.

The fiber glass laminate was made from 9 plies of United Merchants Style 1000—114 glass cloth and American Cyanamid Co. resin, Laminac 4117 laminated under 14 p.s.i. pressure. It was made by the Material Laboratory, N.Y. Naval Shipyard.

Linoleum cements consisting of two types were included because they are usually readily available in most naval installations. Their mechanical properties are described in reference (4) and (5). Linoleum cement reference (4) develops not less than 11.9 p.s.i. in tensile shear under ordinary conditions and after two hours immersion in four percent salt water solution develops a minimum of 5.95 p.s.i. in shear. The minimum required tensile shear strengths for the fire retardant linoleum cements are approximately 1.85 p.s.i. and after two hours immersion in salt water there is a minimum requirement of approximately 2.77 p.s.i. Fire retardant cements are specified by reference (5).

Double planking cements were included because these materials are non-hardening, waterproof, preservative compounds for use between inner and outer planking of double planked hulls and on other faying surfaces of wooden vessels which prevent the passage of water and also serve as a barrier to the spread of decay. Two types are usually used. They are: type I—for use without fabric and type II—for use with fabric. These products are described in reference (6).

Hot melt or low melting point asphalts, resorcinol, urea, hydraulic cement, synthetic rubber—coal tar resin, latex-resin, resin emulsion, polyvinyl acetate resin and epoxy resin comprise the remaining adhesive compounds in the group.

In order not to betray commercial confidences, the manufacturers' product is given a laboratory code letter designation as listed below by groups in table I.

TESTS AND RESULTS

Compatibility. The first step in the study was the determination of compatability of the adhesives with STYROFOAM No. 22, and STYROFOAM No. 33 in order to eliminate promptly those adhesives which obviously were incompatible. This was done by applying the adhesives in accordance with the manufacturer's instructions to a small piece of STYROFOAM. An additional piece of STYROFOAM was placed on top to form a "sandwich." After 48 hours, the "sandwich" was examined for adverse effects (dissolving or softening by the adhesive). This screening test eliminated from further consideration the following cements for the indicated reasons:

Sample Designation	Effect on STYROFOAM
O (Low melting asphalt)	Melting
S (Type II double planking cement)	Considerable softening and dissolving
T (Type II double planking cement)	Considerable softening and dissolving
U (Type I double planking cement)	Considerable softening and dissolving
X (Resin-solvent type)	Considerable dissolving
Y (Linoleum cement—regular)	Considerable dissolving
Z (Linoleum cement—fire retardant)	Considerable dissolving

A shear test was then conducted on the remaining adhesives to screen out low shear strength adhesives. Extremely low shear values (0.5—3.0 p.s.i.) eliminated the following adhesives:

Sample Designation	Remarks
A (Type I double planking cement)	These materials are usually formulated to yield a flexible bond and to provide a sliding shear action.
B (Type I double planking cement)	
D (Type I double planking cement)	
E (Type I double planking cement)	
R (Type I double planking cement)	
P (Type II double planking cement)	
N (Low melting asphalt)	

Water permeability—The method specified for double planking cements was used and is described in reference (5). It consists essentially of having a powerful desicant on one side and water on the other side but neither in contact with a membrane composed of a fabric coated with the cement, adhesive or bonding agent under test. The result is reported as milligrams per square centimeter, per 24 hours. The specification, reference (5) permits a maximum water permeability of 15 mg per sq cm per 24 hour for type I (use without fabric) and 3 mg per sq cm per 24 hours for type II (use with fabric). The results of test are shown in table II.

Shear strength—The final shear values were determined on specimens of STYROFOAM (2½"x3" x1") which were bonded to STYROFOAM, plywood and glass laminates. The bonded test specimen was made with a 1-inch lap resulting in a bonded area

TABLE I.

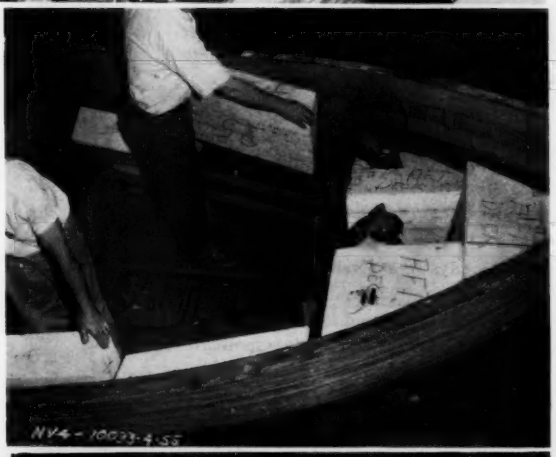
Lab Designation	Remarks
	Linoleum Cements
Y	Stock material—regular grade (MIL-C-15200A)
Z	Stock material—fire retardant grade (MIL-C-15201A)
	Double Planking Cements
A	For use without canvas—Type I (MIL-C-16245A)
B	For use without canvas—Type I (MIL-C-16245A)
D	For use without canvas—Type I (MIL-C-16245A)
E	For use without canvas—Type I (MIL-C-16245A)
R	For use without canvas—Type I (MIL-C-16245A)
U	For use without canvas—Type I (MIL-C-16245A)
C	For use with canvas—Type II (MIL-C-16245A)
P	For use with canvas—Type II (MIL-C-16245A)
S	For use with canvas—Type II (MIL-C-16245A)
T	For use with canvas—Type II (MIL-C-16245A)
	Hot Melt Type
N	Low melting point asphalt
O	Low melting point asphalt
	Cold Set Type
F	Resorcinol resin
G	Urea resin
L	Hydraulic cement
M	Hydraulic cement and asphalt emulsion
A-A	Epoxy Resin Type
	Drying Type
H	Mixture of GRS and coal tar resin
I	Mixture of latex and resin
J	Polyvinyl acetate in solvent
K	Resin-emulsion
V	Polyvinyl acetate in solvent
W	Polyvinyl acetate in solvent
X	Resin—Solvent type

of 3 square inches. The samples were allowed to stand at least 48 hours after preparation. Shear strength determinations were made at room temperature (70°F); after 16 hours exposure to 120°F; after 16 hours exposure to 0°F; and after 7 days immersion in a 4% synthetic sea water solution. The test specimens, upon removal from the various exposures, were immediately sheared in a Baldwin-Tate-Emery Load apparatus with the load applied at a rate of 1 inch per minute. These results are shown in table II.

DISCUSSION

There are some naval applications wherein adhesives are desired to be used which do not set hard. This is so in the case of double planking compounds, particularly the Type I materials. A flexible bond is obtained from them which provides for a sliding shear action with the "working" of the hull. In this study, shear values between 0.5 and 3.0 p.s.i. were obtained in most cases with the double planking compounds. Such low values are obviously unsuitable for applications where shear strength is of importance. There may be certain instances when it is desirable to install STYROFOAM with a flexible bond adhesive and the double planking compounds may be suitable for this purpose in spite of their low shear strength.

The minimum of 15 p.s.i. for shear strength was arbitrarily set at this value for the reason that shear failures begin to occur in STYROFOAM at 16-17 p.s.i.



Some of the adhesives included in this study were two and three-part materials. The ingredients of these must be measured or weighed and mixed immediately before use. Usually these have limited pot life which may introduce fabrication difficulties. However, two of this type, resorcinal and epoxy adhesives, both developed good shear strengths.

Only one adhesive, L (a hydraulic cement), exceeded the maximum allowable water permeability requirement for double planking cements.

TABLE II
Results of Shear and Water Permeability Tests

Shear tests (psi)	Tentative (min) Limits	Double Planking Cement	Resorcinol	Urea	GRS and Coal Tar	Latex and Resin	Polyvinyl Acetate	Resin Emulsion	Hydraulic Cement	Hydraulic Cement and Asphalt	Polyvinyl Acetate	Polyvinyl Acetate	Epoxy
At room temperature (70°F)		C	F	G	H	I	J	K	L	M	V	W	A-A
#22 Styrofoam bonded to itself	15	18.2	18.6	18.3	17.4	2.2	19.8	17.4	16.0	*	18.7	18.2	17.9
#22 Styrofoam bonded to Douglas Fir	15	24.8	20.2	24.7	16.6	3.7	28.0	20.8	12.1	*	30.0	28.7	29.1
#22 Styrofoam bonded to glass laminate	15	7.6	20.8	24.2	23.0	1.5	31.1	23.2	24.3	9.4	31.8	31.8	22.4
#33 Styrofoam bonded to itself	15	19.9	21.5	19.9	18.9	11.1	19.1	21.6	19.5	*	20.2	21.2	24.1
#33 Styrofoam bonded to Douglas Fir	15	25.6	27.3	25.6	14.9	2.6	29.7	22.4	6.0	*	34.3	32.4	31.1
#33 Styrofoam bonded to glass laminate	15	5.0	20.6	25.0	22.9	0.53	29.2	22.6	14.2	8.6	31.4	30.9	30.1
After 16 hours at 120°F													
#22 Styrofoam bonded to itself	15	17.8	17.4	18.3	15.8	4.4	19.0	17.0	17.4	*	16.7	17.9	17.0
#22 Styrofoam bonded to Douglas Fir	15	26.1	22.2	24.2	18.3	2.5	29.6	20.8	13.7	*	29.4	28.6	24.5
#22 Styrofoam bonded to glass laminate	15	***	19.3	19.0	***	0.83	28.1	***	16.8	6.8	27.2	27.1	25.0
#33 Styrofoam bonded to itself	15	18.2	17.2	21.8	16.8	11.9	18.1	20.9	20.3	*	22.3	21.3	24.9
#33 Styrofoam bonded to Douglas Fir	15	22.6	25.0	24.0	15.2	2.1	25.7	20.2	6.4	*	31.2	31.6	32.3
#33 Styrofoam bonded to glass laminate	15	***	12.7	22.0	***	0.87	21.6	***	14.6	4.1	33.0	31.5	30.3
After 16 hours at 0°F													
#22 Styrofoam bonded to itself	15	19.9	17.7	18.3	17.3	2.0	18.6	17.8	13.1	*	18.7	18.5	18.8
#22 Styrofoam bonded to Douglas Fir	15	23.8	22.7	24.3	19.2	4.6	29.4	24.5	11.6	*	29.5	30.7	26.9
#22 Styrofoam bonded to glass laminate	15	***	26.0	26.4	***	2.1	31.4	***	9.4	14.1	33.9	28.2	26.3
#33 Styrofoam bonded to itself	15	18.7	21.6	20.7	19.8	7.7	20.9	21.0	21.2	*	23.7	22.8	24.2
#33 Styrofoam bonded to Douglas Fir	15	25.6	29.4	25.5	23.7	3.3	33.6	26.1	11.4	*	32.3	30.9	29.9
#33 Styrofoam bonded to glass laminate	15	***	14.4	25.0	***	0.90	26.4	***	7.2	11.3	31.7	33.6	29.4
After 7 days in 4% salt H_2O Solution													
#22 Styrofoam bonded to itself	15	17.6	19.8	18.2	10.4	**	18.4	17.9	16.1	*	19.3	19.6	18.8
#22 Styrofoam bonded to Douglas Fir	15	18.6	26.1	25.8	10.7	2.4	25.1	11.4	4.3	*	26.8	33.8	31.0
#22 Styrofoam bonded to glass laminate	15	***	23.2	5.7	***	**	24.3	***	**	8.5	29.9	24.2	22.9
#33 Styrofoam bonded to itself	15	21.2	17.6	20.9	13.4	7.2	19.4	18.4	12.9	*	22.5	21.0	26.5
#33 Styrofoam bonded to Douglas Fir	15	18.3	27.9	25.6	21.1	1.2	25.4	16.7	6.6	*	28.1	29.1	27.6
#33 Styrofoam bonded to glass laminate	15	***	13.8	8.9	***	**	24.2	***	0.93	9.4	30.2	26.4	29.8
Water Permeability (mg/sq. cm/24 hrs.)	15	0.593 (Max)	0.692	4.063	8.038	0.162	0.680	0.104	15.58	2.751	0.881	0.402	4.7
Glue Line Thickness (approx.) inches	1/8	1/16 (Max)	1/64	1/64	1/64	1/32	1/64	1/32	1/8	1/8	1/64	1/64	1/8

*Test not conducted because of poor showing in preliminary investigation.
**Fell apart in handling.
***Insufficient adhesive on hand.
——Underlined shear values represent adhesive failures.

One adhesive, I, yielded acceptable shear strength values in preliminary tests. For this reason, it was included in the group subjected to complete examination. The very low values shown in Table II were obtained in later tests and were apparently caused by the brief shelf life properties of the adhesive.

Adhesives J, V and W are examples of one-part adhesives which are easy to apply in that they require no "on-the-spot" mixing and do not require immediate use to prevent loss by premature setting. These adhesives do contain undesirably flammable solvents, but this hazard can be overcome by the use of suitable safety precautions. Their nature is not such as to exclude their naval use.

Accepting as an arbitrary value a minimum of 15 p.s.i. in shear strength, adhesives J, V, W, F and A-A yielded satisfactory values under all test conditions. All failures for these test samples took place in the material. Adhesive A-A, because of very high viscosity holds STYROFOAM to vertical or overhead surfaces while it cures. The remaining adhesives yielded a number of shear values under 15 p.s.i., the low values in all cases being due to adhesive failures.

CONCLUSIONS

1. Of those adhesives comprising the drying type tested, the polyvinyl acetate compositions yielded superior values under all conditions of test.

2. In general, the resorcinal, epoxy, and polyvinyl acetate compositions are considered satisfactory for bonding STYROFOAM.

3. The linoleum cements tested were incompatible with STYROFOAM because of excessive solvent attack.

4. The double planking cements were unsatisfactory because of low shear strengths.

5. The hot melt or asphalt types tested yielded low shear values and caused excessive melting of STYROFOAM.

6. The cold setting adhesives showed some variability in shear results and in one case gave low values.

7. The other adhesives tested failed in one or more of the features of shear strength, waterproofness, durability, compatibility, good handling features, and flexibility.

ACKNOWLEDGMENTS

The authors desire to thank the Bureau of Ships, Department of the Navy for permission to publish these data. Acknowledgment is made to the following who contributed to the technical aspects of this article: Mr. J. B. Alfers, Mr. L. E. Sieffert, Mr. J. Alpert, Mr. J. G. Kuenzel, Mr. A. Rapavi, Mr. J. Chilcote, and Mr. J. D. Dwinelle and Mr. R. Hartley. The assistance of suppliers of materials for tests is also acknowledged.

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(3) Military Specification, MIL-P-0016591C (Ships), 21 Jan., 1954 for Plastic Material, Cellular Polystyrene.
(4) Military Specification, MIL-C-15200A, Cement Linoleum.
(5) Military Specification, MIL-C-15201A, Cement Linoleum (Fire Retardant).
(6) Military Specification, MIL-C-16245A, Cements, Sealing (Double Planking, Preservative).

The Bureau of Ships has announced the development of a new plastic pipe called Polyvinylchloride for use in emergency pipe repairs. Available in sizes up to four inches, it can be threaded or it can be installed by the use of slip fittings. Polyvinylchloride can withstand internal pressures of 1,500 pounds; for higher temperatures (over 200° F) a special version is available. It is practically immune to weather, salt water and oxidation, and is so flexible as to eliminate in many cases the need for special joints such as T-joints.

THE FORMABILITY OF ALUMINUM ALLOYS

ACKNOWLEDGEMENT

In this article D. A. Barlow, of the Research Department of Aluminium Laboratories Limited, discusses the problem of forming aluminum alloys from a theoretical point of view, in order to establish a sound basis for the great variety of forming operations now used in industry. Reprinted from the 11 May, 18 May, and 25 May, 1956, editions of "Engineering."

IN THE MANUFACTURE of any article, it is generally fairly easy to decide what forming operations, such as bending and deep drawing, are necessary, and ample information is available on the appropriate technique and equipment. In the case of metals such as brass and mild steel, there is also a wealth of experience to draw upon. Little difficulty is met with in deciding how much deformation the material can withstand in each operation, so that the number of operations and intermediate anneals (if any) can be determined and the tools made without fear that the demands on the material are excessive. Rules of thumb are often available giving reasonably good results with the more commonly used materials. With aluminum alloys, however, while there are a few such rules which can be applied to commercially-pure aluminum in the soft temper, there are no rules applicable to other tempers or to other alloys, and previous experience is often scanty.

The aluminum alloys have widely different ductilities. The demands made on the material also vary, so that an alloy which is the best for one operation may not be the best in another operation involving a different stress system. For example, commercially-pure aluminum in the soft condition is one of the most ductile aluminum alloys for stretch forming, but in deep drawing it is surpassed by a number of other alloys, some of which are rather poor in stretch forming. If tool and product designers are to use the most suitable alloy and the fewest number of operations, they must know the forming limits of ductility of each alloy and temper in each type of operation. These limits can be determined experimentally, but this involves an enormous amount of work even when the number of alloys and operating variables, such as tool dimensions, etc., is small; and without the theoretical background or knowledge of the mechanism of the forming processes it is impossible to apply the results obtained to other alloys and tools. The need for a theoretical study of forming operations is thus apparent, both to enable intelligent use to be made of existing data, and to assist in the solution of practical difficulties. A knowledge of the behavior of the metal in the common forming operations would also be a useful guide in assessing operations on which no previous experience is available.

The present article is based on a study of the literature and on experimental investigations carried out at Aluminium Laboratories Limited. Forming operations are classified according to type, and the limits to which the various alloys may be formed are determined. Discussion is confined to operations carried out by the manufacturer of the end product; fabricating processes such as rolling, extrusion and tube drawing are excluded. Spring-back and internal stresses after forming are not discussed, and forming loads are only considered in so far as they affect the forming limits.

In considering whether a given part can be

formed, there may be more than one type of operation involved, but it is generally fairly easy to decide which is the controlling one. Thus a deep cup-shaped part may involve deep drawing, curling of the rim and raising a design on the base, the deep drawing being the most severe operation. On the other hand, in a shallow cup with small corner radii the bending over these radii may be the limiting factor.

CLASSIFICATION OF TYPES OF FORMING OPERATION

Forming operations may be classified as follows:

(1) Stretching or tensile.
(2) Shrinking or compressive.
(3) Bending.
(4) Deep drawing.
(5) Ironing.

Operations such as coining and impact extrusion are omitted because the forming limits are set by the tools rather than by the material.

SECTION I: STRETCHING OR TENSILE OPERATIONS

BEHAVIOR IN TENSILE TESTS

Before discussing the various tensile forming operations, it is useful to examine the behavior of a tensile test piece under load (Fig. 1). The elongation of a tensile test piece consists of two parts: a general or uniform elongation, and the local elongation at the neck at fracture. The general elongation is dependent primarily on the rate of work hardening and the uniformity of the material, and in a parallel uniform specimen is the elongation at maximum load. Up to the maximum load the material strengthens as a result of cold work at a greater rate than it weakens due to thinning, so that the load increases and elongation takes place uniformly. At the maximum load the rate of strengthening due to work hardening is equal to the rate of weakening due to thinning; beyond it the material is still work hardening but is thinning more rapidly, and the load begins to fall. If the material were perfectly uniform and the test piece of constant cross-section, uniform extension would continue after the maximum load had been reached, until the whole test piece disintegrated at fracture. In practice, no such uniformity is obtained, so that, beyond the maximum load, deformation ceases except at the weakest point; and since the load is dropping it continues at that point until fracture. Because necking occurs at the weakest point, the remainder of the specimen does not reach its maximum load or ultimate tensile stress, and therefore does not quite develop its full general elongation.

The local elongation is the elongation at fracture on zero gauge length and is a measure of the total deformation the material can withstand before fracture. It is equal to the difference between the original area A_0 and the final Area A_1, divided by the final area, or $\frac{A_0 - A_1}{A_1}$, if there is no volume change. The maximum

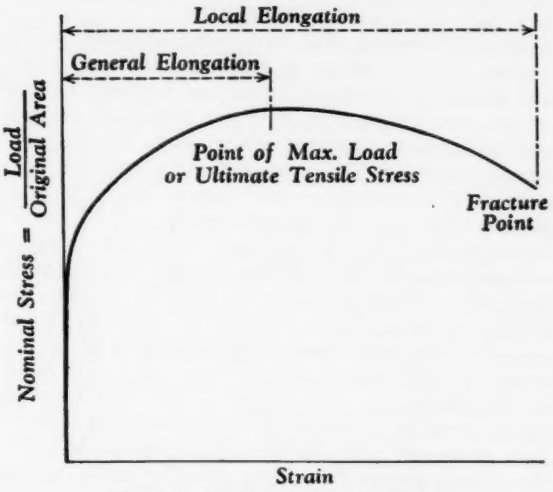


Figure 1. Tensile stress-strain curve.

volume change is about 0.2 per cent and can be ignored. It should be noted that the stress at the neck of a test piece is not pure uniaxial tension, as it was prior to necking, but is triaxial tension (unbalanced). It is well known that ductility under triaxial tension is less than under uniaxial tension. If uniaxial tension only is present and necking can be prevented, as in some types of forming operation, deformation in excess of the local elongation at the neck of a tensile test piece can be obtained.

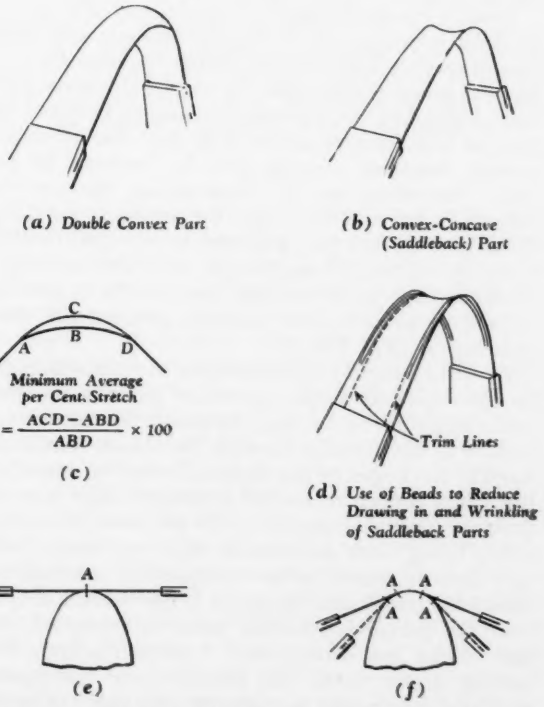


Figure 2. Stretch forming, for making large radius curves in sheet.

STRETCH FORMING

Stretch forming (Fig. 2) is often used for making curves of large radius in sheet and sections, where the difficulty in forming by normal bending methods is not lack of ductility but the large and variable spring-back—a problem which does not arise in stretch forming. The process is also used for parts with double curvature which cannot easily be made in any other way. The sheet or section to be formed is gripped firmly at opposite ends and wrapped around a punch which is then pressed into the material, thus stretching it to the desired profile. The grips may be pivoted so that tension is always transmitted in line with the unsupported ends of the material, or they may be fixed when used with sheet. In the latter case, the edges of the jaws must be given a radius of at least 15 to 25 times sheet thickness, to avoid failure at the edge of the jaws, unless the stretch required is a light one. The radius should be smooth but unlubricated since the friction over the radius reduces the stress concentration at the edge of the grips.

In forming single curvature parts, the material is generally draped or wrapped round the punch, usually with an initial tension up to the proof stress, and the punch is then given a small traverse to "set" the curve, i.e., just sufficient stretch to eliminate appreciable spring-back. Often less than 4 per cent stretch is needed, so that material of almost any alloy or temper can be formed. If the material is not draped round the punch, the stretch required to form the part is considerably greater.

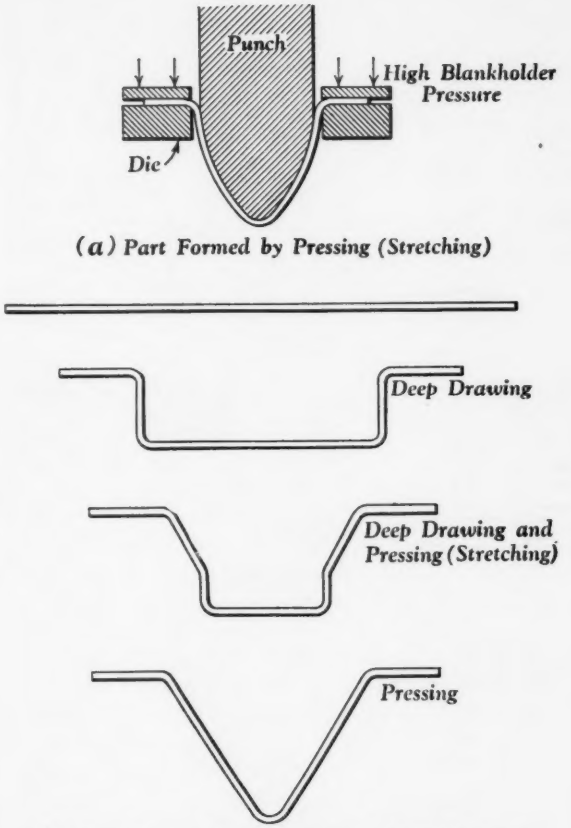
Double curvature parts (Figs. 2*a* and 2*b*) may be of double convex or of convex-concave curvature (saddleback). The average stretch required for such parts is much greater than for single curvature parts and is equal to the difference in length between the longest and shortest paths (Fig. 2*c*); the maximum stretch required exceeds this by perhaps 50 per cent, depending on the dimensions, because the stretch is not uniform over the contour. An additional stretch of 1 to 2 per cent is required to eliminate spring-back. Longitudinal wrinkles may form on saddleback parts but they can usually be avoided by adding beads to the punch to prevent the sheet drawing in (Fig. 2*d*).

Forming Limits—The maximum stretch which can be developed in single curvature parts is the general elongation in tension, although this amount of stretch is not usually needed. To obtain maximum stretch, the edges of the material must be smooth—the stress concentrations at a sheared edge may reduce the available stretch by 50 per cent, the strong alloys being more sensitive to edge conditions. Fracture usually occurs in the unsupported material between the punch and the grips. If the sheet is draped over the punch before the latter is traversed, the part "locks" on to the punch if friction is high. The locking action limits the stretch over the punch, and good lubrication is required with parts of single curvature to obtain a stretch approaching the general elongation. The lubricant should be of the "boundary" type, such as soap, waxes, etc., as speeds are very low. Where a fairly large stretch is needed, as on double curvature parts, it may be useful if the punch can be arranged to move during the draping instead of afterwards. With parts of sharp, and especially double curvature, some friction at the crown of the punch is required to prevent local deformation at that point and penetration of the sheet by the relatively sharp punch.

The limiting stretch normally obtainable under suitable conditions on double curvature parts is the general elongation under biaxial tension. Swift[1] has shown that this general elongation can be determined from the true-stress/true-strain diagram in simple tension if the ratio of the two tensions is known. Using this method it can be shown that the general elongation under balanced biaxial tension (i.e., the two tensions being equal) is equal to the simple tensile general elongation; under intermediate conditions (unbalanced biaxial tension) the general elongation may be up to 20 per cent greater or 10 per cent less than the simple tensile general elongation. Thus, for practical purposes, it is not necessary to know the ratio of the two tensions, because the departure from the simple tensile general elongation is not large and will be covered by the usual "safety factor" necessary to allow for variations in material.

Dorn and Lotze[2] have shown that it is sometimes possible to obtain stretches exceeding the general elongation, and approaching the local elongation, particularly when forming at elevated temperatures. In the latter case "necking down" often sets in, but is spread over a large area, so that an acceptable part is produced. Sachs and Espey[3] have concluded that the stretch obtainable, particularly at elevated temperature, is a complex function of the geometry of the part, the movement of the ram and grips, and the friction between the part and the punch, and it seems that the conditions used by Dorn and Lotze happened to be particularly favorable. A possible mechanism whereby a stretch approaching the local elongation can be developed is given below.

Consider the sheet at the moment of contacting the punch (Fig. 2*e*). Deformation will be concentrated at the line of contact. If punch friction is high, the sheet will "lock" on to the punch and deformation will then continue on either side of the area of contact (A-A, Fig. 2*f*) as the sheet is wrapped round the punch. If the correct tension at each instant is applied to the sheet and if it is wrapped round the punch at a suitable speed, the stretch at either side of the area of contact with the punch can exceed the general elongation and be well in the "necking" range, provided that the "neck" contacts the punch before failure can take place. This necking would occur to each element of the sheet in turn as the forming cycle proceeds so that a uniform stretch exceeding the general elongation would be obtained. With single curvature parts, the necks at points A-A



(a) Part Formed by Pressing (Stretching)

(b) Part Formed by Pressing and Deep Drawing

Figure 3. Pressing, with punch and die.

would form straight across the sheet, so that the conditions for exceeding the general elongation would be very critical and failure would occur very easily. On the other hand, with double convex parts the necking area would be some form of closed curve, consequently the sheet would be less likely to fail. With parts of severe double curvature, conditions would be very critical and very high punch friction would be required. The above mechanism would account for the fact that Dorn obtained the greatest stretches on parts of moderate double curvature and the least stretches on parts of single and severe double curvature.

The most ductile condition for stretch forming is generally the annealed condition, but it should be noted that some heat-treated alloys have as much general elongation in the naturally-aged as in the annealed state. The effect of directionality can be ignored, as this is generally small.

PRESSING

The term pressing (Fig. 3) is often applied loosely to include any article formed in a press. "Pressing" is used here to denote the operation whereby sheet is formed between a punch and die by stretching. Superficially, pressing resembles deep drawing, many operations being a combination of the two processes: but whereas in deep drawing the sheet is allowed to flow freely into the die, in pressing, movement of the blank as a whole is prevented by a spring- or pneumatically-loaded blank holder. The blank holder pressure must therefore be very high; alternately, the same effect can be obtained if a large blank is used so that the flange prevents drawing in.

If the punch is flat-bottomed, or substantially so, shallow pressings only can be produced, since the walls have to take all the stretch. Deep flat-bottomed parts must be drawn. Where the punch is conical, parabolic, etc., in shape as compared to flat-bottomed, the sheet must not be allowed to draw in freely or puckers will form over the punch (not to be confused with wrinkling over the die). With soft materials and a hemispherical punch it is usually possible to allow the sheet to draw in, i.e., to deep draw the material, as the deep-drawing load is sufficient to stretch the sheet over the punch without puckering; but since the stretch is considerable, only alloys with considerable general elongation are satisfactory.

Forming Limits—As pressing is simply stretch forming, the forming limit is the tensile general elongation. Calculation of the amount of stretch required for a given part may be very difficult, especially where some drawing in of the sheet takes place. The stretch will vary from point and point and although the average stretch can be calculated if there is no drawing in of the sheet, the maximum stretch cannot. Many parts cannot be formed in one operation by stretch alone, because the amount of stretch required would be excessive, and they are therefore formed in stages by drawing followed by stretching (Fig. 3b). In these cases the stretching, and therefore the general elongation, is the limiting factor.

BEADING

Beading (Fig. 4) may be done in a press with metal punch and die (Figs. 4*a* and 4*b*), between shaped rolls (Fig. 4*c*), or in the rubber die press (Figs. 4*d* and 4*e*). Where discontinuous beads are formed in sheet, conditions are similar to those in pressing. If the area of sheet surrounding the bead is large, no drawing in of the metal can take place, and the bead is formed by two-way stretching. The average stretch required can be determined from the profile of the bead. Sharp corners should be avoided, and it should be remembered that in the case of a flat-bottomed bead the flat surface stretches very little, so that the sides have to take most of the stretch; a rounded profile is therefore to be preferred. Where the surrounding area of sheet is small and clamping forces are not high, some drawing in can take place and slightly deeper beads can be obtained. Where a continuous bead is formed near the edge of a sheet, the material is free to draw in unless the tools are very rough. In this case the bead is formed by bending rather than stretching,

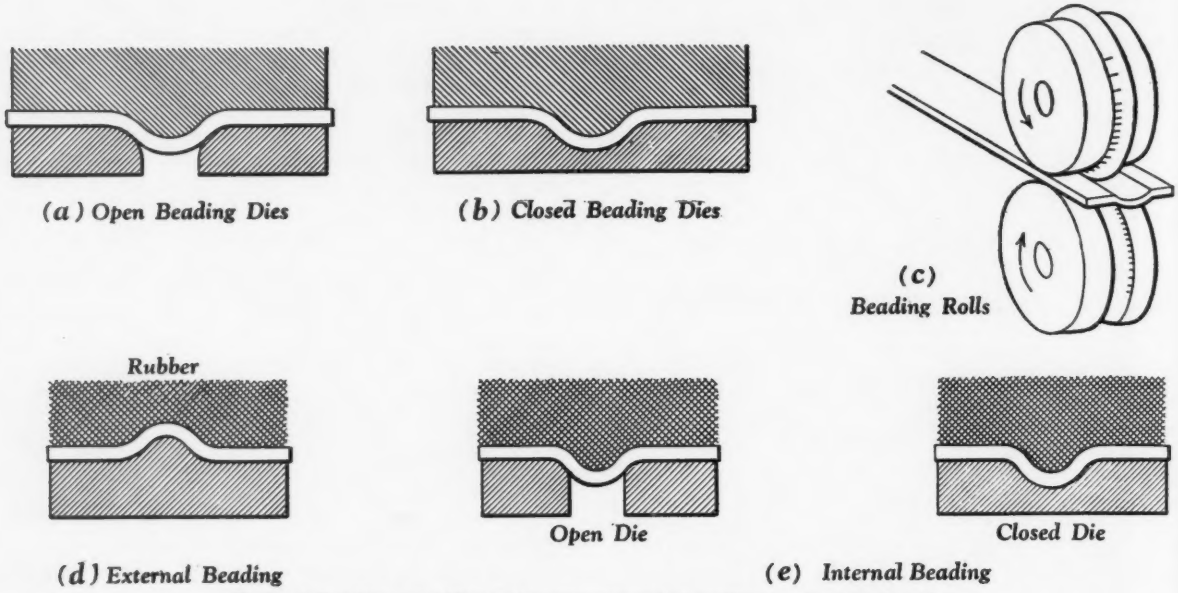


Figure 4. Beading by rolling and pressing; rounded profiles are to be preferred.

the only limit to the depth of the bead being the bend radii.

Where continuous circumferential beads are formed on cylindrical parts, they may be made by rolling, by expansion of a segmented punch, or by fluid pressure. Generally, the cylinder is free to contract longitudinally, so that the metal is subjected to circumferential tension only. If the material is not free in the longitudinal direction, two-dimensional stretching takes place. Where fluid or rubber pressure is used, and profiles other than that of the usual bead are formed, the operation is called expanding or bulging (Fig. 5).

Figure 5. Bulging.

Dorn, Cunningham and Thomsen[4] have carried out beading tests in a rubber die press on a variety of aluminum alloys and have found that if the bead is of circular section, as is usually the case, the stretch over the bead is almost uniform. Under these conditions it would be expected that the general elongation would determine the maximum depth of bead obtainable, but in fact the limiting stretch was only about half the general elongation of the material. Failure occurred at the junction of die radius with the bead radius before the general elongation was reached over the bead surface, perhaps because of the complicating factors of the bending and the radial pressure of the rubber.

EMBOSSING

The process of embossing or raising is used for producing designs, lettering, etc., on sheet (Fig. 6) and may be combined with other press operations. It is essentially two-dimensional stretching, as the surrounding sheet will prevent drawing in so that the operation resembles beading and will have a

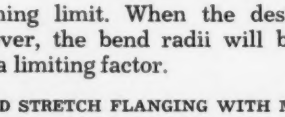


Figure 6. Embossing or raising.

similar forming limit. When the design must be sharp, however, the bend radii will be small, and this may be a limiting factor.

FLARING AND STRETCH FLANGING WITH METAL TOOLS

Flaring is the expanding of the mouth of a tube or other cylindrical part by means of a tapered plug or punch (Fig. 7*a*) or by means of a rotary swaging tool. This gives the equivalent of circumferential uniaxial stretch and the general elongation determines the limiting stretch. However, the general elongation in the circumferential direction on tubes may be somewhat less than that in the longitudinal direction, which is the direction in which the material is normally tested. For the maximum stretch, the edge must be smoothly finished.

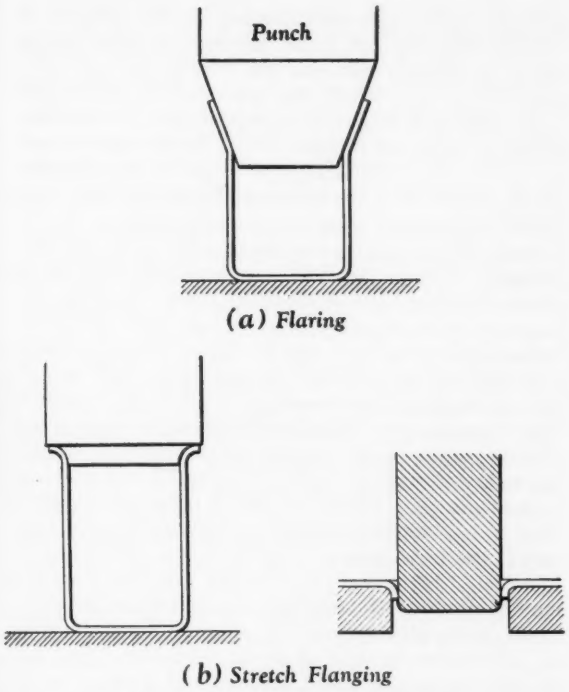


Figure 7. Flaring and stretch flanging.

The forming of stretch flanges on cylindrical parts and the flanging of holes in sheet, Fig. 7*b*, are similar to flaring since the radius is usually generous and does not limit formability. In the flanging or flaring of spun or deep-drawn parts it should be remembered that the walls have already received considerable cold work and may have very little general elongation. If a segment is being flanged, instead of the full circle, the free ends of the segment do not stretch, so that on small segments the amount of stretch is reduced and higher flanges can be obtained.

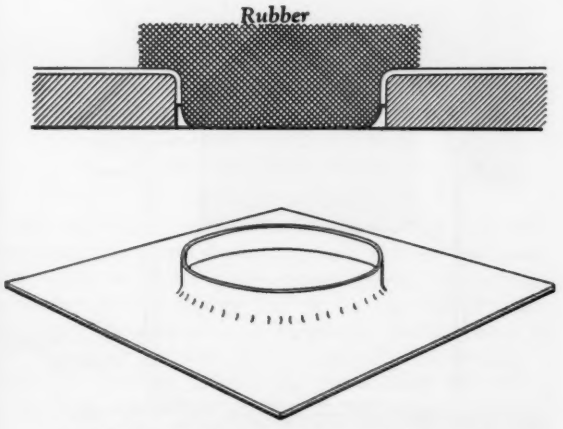


Figure 8. Stretch flanging in rubber die press.

STRETCH FLANGING WITH THE RUBBER PRESS

When rubber is used instead of a metal tool for flanging, as in the flanging of lightening holes in sheet parts (Fig. 8), it is possible to get much greater deformation than with metal tools. If the flange radius is generous, the material fairly uniform and the edge of the hole smooth, the deformation possible on this edge exceeds the general elongation and frequently approaches the local elongation. It is known that the friction between the rubber and the metal is very high and that little if any relative motion occurs. In these circumstances all deformation of the sheet follows that of the rubber. The latter, being highly elastic, resists local stretching, and so equalizes the deformation of the sheet, unlike metal tools, which allow local necking to take place. The stage at which local deformation followed by fracture begins depends on the friction between the rubber and the sheet. Dorn, Cunningham and Thomsen[5] found that the maximum stretch obtainable exceeded the general elongation and was about half the local elongation for annealed alloys, up to a maximum value of 65 per cent stretch, and equal to the local elongation for heat treatable alloys, up to a maximum value of 35 per cent stretch. As in flanging with metal tools, when a segment only is being formed, the free edges do not stretch, and if the segment is less than about 60 deg. the reduction in stretch allows higher flanges to be produced.

CURLING AND WIRING

"Curling" consists of the turning over of the edge of a sheet part to form a hollow rim (Fig. 9*a*); where a wire or rod is incorporated, the operation is termed "wiring" (Fig. 9*b*). The operations are performed by pressing in a die (Fig. 9*c*) or by spinning (for circular parts only). Where the part is straight, bending only is involved (this is dealt with later, under the appropriate section). Curved parts involve stretching and shrinking of the sheet in addition to bending. If the bend radius is small it may be the critical factor, but if it is generous the ductility in stretching and shrinking must be considered. In forming a rim on the outside of a curve (Fig. 9*d*) the sheet is first stretched to the maximum diameter of the rim and then shrunk back to approximately its initial diameter. The percentage deformation is therefore readily determined and the general elongation will give the limiting stretch if the edge is smooth. As with flanging and flaring, it should be remembered that spun or deep-drawn parts have already received considerable cold work and may have very little general elongation. The shrinking is not so critical, as the compressive ductility of aluminum alloys is always as great as, and generally much greater than, the tensile ductility so that if the material will withstand the stretching of the rim it will have ample compressive ductility.

In curling operations, a possible form of compression failure is by buckling. If the rim is wired, the sheet is supported by the wire on one side and the

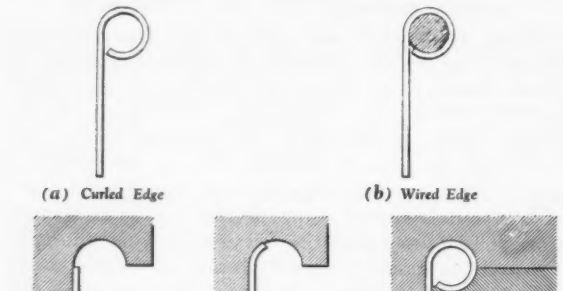


Figure 9. Curling and wiring; wiring is used to prevent buckling.

tool on the other, so that buckling is prevented. With rims of the proportions normally used, however, buckling is seldom experienced whether the rim is wired or not. In forming a rim on the inside of a curve (Fig. 9*e*) the sheet is first compressed and later stretched. The conditions will therefore be slightly more severe than before because the sheet is further cold worked before stretching (which is the critical operation) is carried out. When curling or wiring by pressing, the edge of the sheet should always be given a slight "lead" (Fig. 9*c*): without this, "peaking" or kinking of the sheet will occur (Fig. 9*f*).

SECTION II: SHRINKING OR COMPRESSIVE OPERATIONS

BEHAVIOR OF MATERIAL IN THE COMPRESSION TEST

In compression, unlike tension, there is no local contraction—any deformation at one point results in thickening the material instead of weakening it, so that further deformation continues elsewhere, i.e., all deformation is general. If a fundamental relation exists between tensile and compressive ductility, the reduction of area in tension calculated on the final area $\left(\frac{A_0-A_1}{A_1}, \text{ where } A_0>A_1\right)$ should compare with the increase of area in compression calculated on the original area $\left(\frac{A_1-A_0}{A_0}, \text{ where } A_1>A_0\right)$. In measuring compression properties, deformation at the ends is restricted and the test piece assumes a barrel shape, owing to friction between the ends of the test piece and the platens. Since the specimen is not in pure compression, it might be expected that the ductility would be reduced. In spite of this the increase of area for most aluminum alloys is as great as and often much greater than the tensile reduction of area.[6] It is worth noting that when compressive failure occurs, it is usually by fracture in shear at about 45 deg. It is probable that in tension any local fissures, weak points or other form of inhomogeneity, whether on a macro or a micro scale, tend to open out and cause failure, with relatively low ductility. In compression, such fissures would close up and have much less effect on ductility. The tensile properties of a material may therefore give little indication of its compressive ductility; thus, many strong alloys are more ductile in compression than would be expected, and material in the fully heat-treated temper is often more ductile than in the solution-treated and naturally-aged temper. If the ends of the compression test piece are lubricated, "barreling" is reduced and the ductility may be doubled, the increase depending on the alloy; some strong alloys, however, show reduced ductility on lubrication in spite of diminished barrelling. Lubrication does not affect the loads in a compression test to a great extent, although it may considerably reduce the loads in other operations where compression is involved, e.g., shrinking of cylindrical parts. In many compressive operations, the limiting factor is not the compressive ductility but buckling of the part.

RIVETING, COLD FORGING OF BOLT HEADS, ETC.

In these operations the rivet or bolt heads may be formed by squeeze or single- or double-blow machines, or by hand or pneumatic hammer when driving rivets in the field. The compressive ductility is

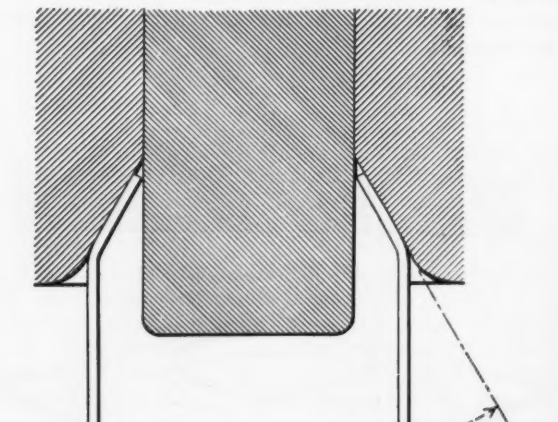


Figure 10. Shrinking.

the limiting factor in each case. The shape of the rivet or bolt head affects the ductility—most snaps or dies partly enclose the material giving triaxial compression, thus increasing the ductility (although to a variable extent) so that it may be safely assumed that a material will form a head if it will withstand the same amount of deformation in a free compression or flattening test.

SHRINKING OF CYLINDRICAL PARTS

The process of shrinking of cylindrical parts (Fig. 10) consists of tapering the mouths and closing over the ends of tubes and other cylindrical parts, and may be carried out by pressing in a die, by rotary swaging tools, or by spinning on a collapsible or offset stationary mandrel, or on "air," i.e., a wooden wedge held by the operator. As the operation is compressive, the wall thickness is increased and there is usually ample ductility. It should be noted that the edge of the material should be fairly smooth —a nick may lead to folding and cracking at that point. Where the shrinking is done by spinning, the maximum shrink is limited by buckling and the skill of the operator. In shrinking in the press, longitudinal as well as circumferential buckling may occur, and to avoid longitudinal collapse it is sometimes recommended that the angle between the shrunk portion and the side wall should not exceed 45 deg. Where considerable contraction is required the reduction is made in steps of 5 to 15 per cent, and to avoid buckling and body collapse a mouth anneal is sometimes given, or the mouth may be heated and then formed while hot.

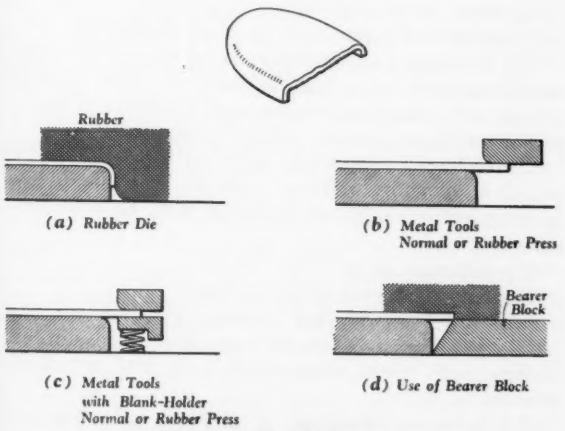

Rubber
(a) Rubber Die
(b) Metal Tools Normal or Rubber Press
Bearer Block
(c) Metal Tools with Blank-Holder Normal or Rubber Press
(d) Use of Bearer Block

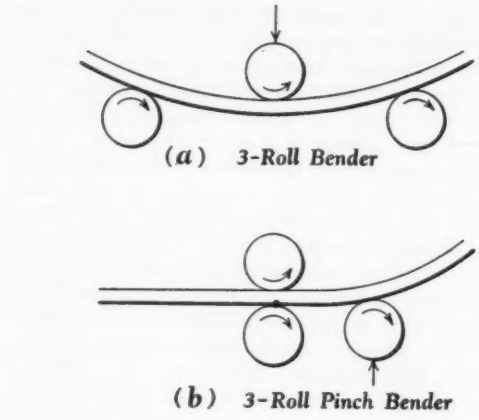
Figure 11. Shrink flanging.

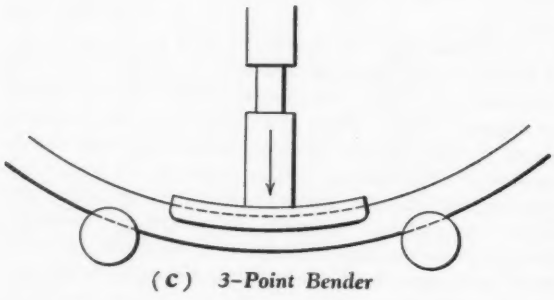
SHRINK FLANGING

The operation of shrink flanging (Fig. 11) may be done in a normal press or in a rubber die press, and consists of flanging convex parts, so that the material in the flange has to be shrunk or compressed. The punch is of metal and the die may be of rubber (Fig. 11*a*) or of metal (Fig. 11*b*) with or without a blank holder for controlling wrinkling (Fig. 11c). If a blank holder is used true shrinking occurs and the depth of flange is limited only by the ductility of the metal in deep drawing, as this is a deep-drawing process. In rubber-die pressing with parts of normal dimensions, no true shrinking (i.e., compression without buckling) can be obtained. When such a shrink flange is formed, wrinkles at first appear and are flattened out later by the high pressure of the rubber. The amount of shrink obtainable depends therefore on the final pressure of the rubber. Dorn, Thomsen and Cunningham[7] have obtained values of limiting shrink of 4 to 7 per cent on a number of alloys in sheet 0.036 in. thick, using ½ ton per square inch rubber pressure. Values can be estimated with sufficient accuracy for other alloys; slightly higher values are obtained with higher rubber pressures, especially on soft materials. The maximum shrink varies a little according to gauge, the thicker gauges giving higher figures. When a slight amount of wrinkling, to be removed by a further operation, is allowable, the above values may be increased to 6 to 10 per cent; at higher shrinkages wrinkling is so severe as to be removed only with the greatest difficulty. If bearer or slipper blocks (Fig. 11*d*) are used the support given to the flange reduces wrinkling and much greater shrink values, of the order of 10 to 25 per cent shrink, can be realized. Methods of removing slight wrinkling include hammering, machine shrinking, or the use of metal (for example, "Cerrobend") wedges. In the latter case the part is formed and the wedges are then placed in position between the flange and the bearer block and pressure is applied, thus removing the wrinkles. When a segment only is being formed the free ends do not shrink, so that if the segment is less than about 60 deg. the effective shrinkage is reduced and higher flanges can be obtained. Various devices are used to avoid wrinkling, such as cut-outs to reduce the segment angle, or crimping to absorb the excess material at suitable points.

SECTION III: BENDING

This process (Fig. 12) includes bending of sheet, sections and tube in three-roll, three-point loading and wrap machines, also straight flanging using a punch and die or rubber die press. Three-roll machines are used for large radius curves, the minimum radius being generally determined by the design of the machine rather than by the material. In three-point loading, the maximum bending moment is at the mid-point, so that although fairly uniform bends are obtained by the use of suitable formers, "peaking" and fracture at the mid-point may occur before the remainder of the material has conformed to the radius—this applies particularly to the high-strength alloys which do not work harden rapidly. Wrap type machines have the advantage that an accurate bend is produced and peaking is prevented. The minimum radius obtainable is limited by the ductility or buckling of the part, and the formers and guides can easily be designed to support the sections so as to minimize buckling.





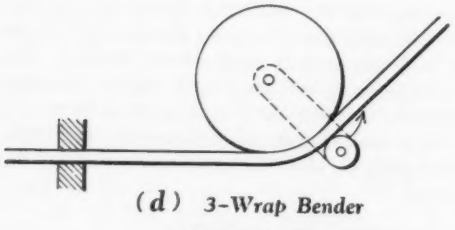


Figure 12. Bending.

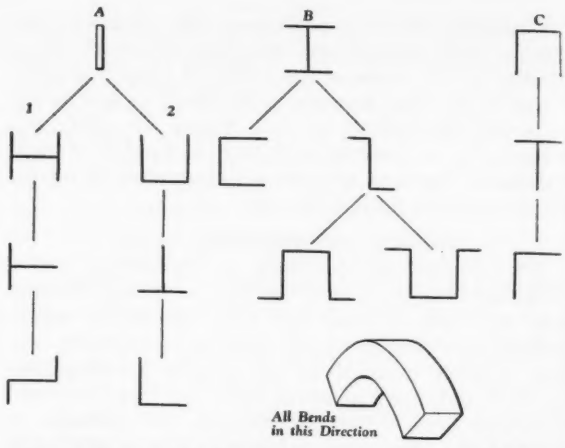


Figure 13. Classification of common sections by methods of failure.

STRUCTURAL SECTIONS AND OTHER OPEN SHAPES

Since aluminum alloys are generally more ductile in compression than in tension, fracture when it occurs is usually in the outer fiber in tension. The common structural sections can be classified according to whether they fail in tension or by buckling (Fig. 13). Referring to Fig. 13, Class A sections generally fail in tension, although buckling may be difficult to prevent on the thinner sections in Class A1. Class C fail by buckling, and in Class B the mode of failure will depend largely on the dimensions of the section. The minimum bend radius for Class C will depend on the support given by the dies. Because the material thickens up in compression, clearance must be provided between the dies and the section, and this will allow some buckling. The minimum bend radii for Class C sections are probably best determined experimentally on a few representative sections so as to obtain empirical relations between the minimum bend radius and section dimensions, since the analysis of plastic buckling problems is usually very difficult.

TUBES

Consideration of the bending of tubes suggests that failure may take place in a number of ways, depending on the wall-thickness: tube-diameter ratio and the conditions of bending. The latter may be classified as follows:

(1) Free bending, with no fitted formers, etc. Data on this method would be useful where small numbers of bends must be made and complete equipment is not available.

(2) External support by grooved formers.

(3) External support by grooved formers and internal support by a flexible mandrel. This method is used in production, where large numbers of bends to the smallest possible radii are required.

(4) External support by grooved formers and internal support by a filler material (e.g., sand, low melting point metal, etc.) which may be compressible.

(5) Internal support by a filler.

The tubes fall into three groups:

(a) Very Thick-Walled Tubing—This behaves like rod in bending and the forming limits are similar. Tubing with these proportions is of little practical interest.

(b) Tubes of Moderate Wall Thickness—Method (1): The tubes tend to flatten and the failure point is that at which flattening is considered excessive. A figure of 5 per cent reduction in diameter is often taken in practice. Method (2): The tube fails as in method (1), but the lateral support given by the grooved former reduces the amount of flattening. Method (3): The mandrel prevents flattening and the outer fibers commence to neck on reaching the general elongation in plane strain, because lateral contraction is prevented and (in contrast with the bending of bars) there is little support from the re-

mainder of the material. Method (4): The failure point depends on the mechanical properties of the filler and failure may take place by flattening or by necking as in method (3). Method (5): Failure occurs by flattening, the minimum-bend radius depending on the properties of the filler.

(c) Very Thin-Walled Tubing—Methods (1) and (2): Failure will take place by buckling due to longitudinal compression. Method (3): Failure will take place in tension, as for tubes of moderate wall thickness. Methods (4) and (5): Failure may take place by flattening or buckling, depending on the mechanical properties of the filler.

SOLID SECTIONS

In the present discussion solid sections are regarded as comprising compact shapes such as rectangular, round or hexagonal bar, etc., where the minimum-bend radius is governed by tensile ductility. The bending of rectangular bars only is examined here, but other compact shapes may be expected to behave in a similar manner.

For rectangular bars the tensile ductility of the outer fiber in bending depends on the width: thickness ratio. Where this ratio is small, say less than 1, the lateral restraint is small, so that as the outer fibers stretch longitudinally they are free to contract laterally, i.e., they are in pure tension; the inner fibers are likewise in pure compression, because they are free to expand laterally. This gives rise to the familiar anticlastic curvature. When the outer fibers reach their maximum load or general elongation, the load on the remainder of the fibers is still increasing. The bending moment on the section as a whole is thus increasing, i.e. the section is stable, so that the outer fibers are supported by the remainder of the bar and deformation continues without local necking or failure over the full length of the bend. Eventually the bending moment reaches a maximum, when the section becomes unstable and local necking followed by fracture occurs. The stage at which the bending moment attains its maximum value depends on the shape of the stress-strain curve, and has been calculated by Dorn and Jelinek[8]; it can be shown that for all commercial aluminum alloys this occurs at an outer fiber strain of 100 to 200 per cent. Observations on gridded rectangular bars show that the material will be bent flat on itself at an outer fiber strain of 75 to 100 per cent, when further bending is impossible. If the section is bent around a former, any local collapse is prevented and fracture only takes place when the local elongation has been exhausted. Dorn, Putman, Julinek and Thomsen[9] found good agreement between bend and tensile-test results in this way for a number of aluminum alloys.

There is evidence from the results of Sachs *et al*,[10] for very narrow rectangular sections where the width: thickness ratio is less than, say, 0.3 (as, for example, strip on edge) that the outer fiber ductility decreases slightly. It is difficult to bend such sections without buckling, but analysis of their behavior would be interesting as the mechanism of failure may differ from that of slightly wider sections. In very narrow sections, the restraint and therefore support given to the outer fibers by the remainder of the bar is less than in slightly wider sections and may be insufficient to enable the full local elongation to be utilized. In infinitely narrow sections there would be no restraint and no support, so that the section would behave as a number of separate fibers, and necking would commence at the ordinary ultimate tensile stress of the outer fiber; the minimum-bend radius would thus be given by the simple tensile general elongation.

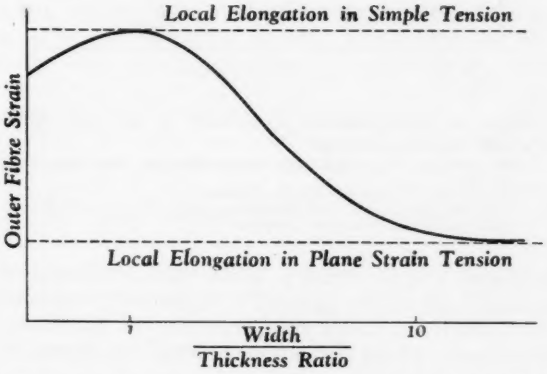


Figure 14. Variation of ductility in bending with width: thickness ratio (after Sachs et al).

SHEET AND PLATE

In the case of sheet and plate the width: thickness ratios are high, and during bending the edges only are free to strain in the transverse direction, so that a transverse tension is induced in the outer fibers. Under biaxial tension the local ductility is reduced, with the result that the minimum-bend radius is also reduced, to an extent which depends on the width: thickness ratio. With increasing values of the ratio the lateral restraint and corresponding lateral tension increase, until at a ratio of 10 to 20 all lateral strain is prevented (except at the edges) and no further loss of ductility occurs (Fig. 14). If the limiting values of minimum bend radii are known for wide and narrow sections, values for intermediate width can be estimated with sufficient accuracy for practical purposes from the general shape of the curve in Fig. 14, which is based on tests by Sachs *et al*.[10]

Dorn *et al*.[9] have shown how the minimum-bend radius for wide sections can be calculated. Consider the true-stress/true-strain curve in simple tension (Fig. 15). Fracture occurs at point A, according to a certain law, the maximum principal stress or maximum shear stress fracture criterion being generally accepted for aluminum alloys; both furnish the same result in this case. For wide sections, where there is no lateral strain, it can be shown that the lateral stress $p_2 = \frac{1}{2}$ longitudinal stress, p_1. Elastic strains are

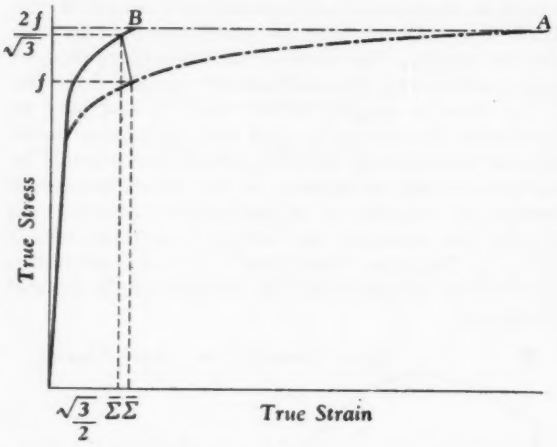


Figure 15. Determination of ductility of the outer fibres of a wide beam in bending.

—— Stress-Strain Curve for Outer Fiber Assuming Von Mises Yield Criterion
—·— Stress-Srain Curve for Simple Tension
– – Fracture Stress Assuming Maximum Shear Stress or Maximum Principal Stress Fracture Criterion

neglected and the stress p_3 in the thickness direction is small and can be ignored. It is generally assumed that aluminum alloys yield according to von Mises' hypothesis, which under plane strain conditions, as in this case, gives $p_1 = \frac{2}{\sqrt{3}}f$, where f is the yield stress in simple tension. The stresses in the outer fiber of a wide section can therefore be derived if the stress values of the simple true tensile curve are multiplied by $\frac{2}{\sqrt{3}}$; if the constant total plastic work hypothesis is used the strain values must likewise be multiplied by $\frac{\sqrt{3}}{2}$, giving the stress strain curve in Fig. 15. Point B, where the critical value of maximum principal stress or maximum shear stress is reached, gives the local ductility of the outer fiber, from which the minimum-bend radius can be calculated.

It is unnecessary to re-plot stress-strain curves; the plane strain ductility is 0.866 × the true strain, corresponding to a true stress of 0.866 × the true fracture stress in simple tension. The true-stress: true-strain curve can be determined approximately from the ordinary stress-strain curve. Thus, up to the ultimate tensile stress, true stress = $(1 + e)$ × nominal stress, where e is the ordinary elongation, $\frac{L-L_0}{L_0}$. The true fracture stress = $\frac{\text{fracture load}}{\text{final area}}$. It is well known that for many materials the true-stress: true-strain curve is approximately a straight line from the maximum load to fracture, so that an approximate curve can be obtained.

It will be realized from the foregoing that the theoretical values for outer-fiber ductility depend on the fracture and yield criteria used, particularly the latter. The author has shown elsewhere[11] that bend-test results appear to throw doubt on the accuracy of von Mises' hypothesis of yielding for some aluminum alloys.

Table I gives a comparison between quoted minimum-bend radii and values calculated as above. The quoted values are for 0.064 in. thick sheet expressed in terms of the thickness t, and were obtained on bend test pieces of ½ in. width, giving a width: thickness ratio of 8, corresponding very nearly to infinitely wide sheet. Calculated values of limiting outer fiber strain of over 75 per cent are given in the table as "flat." It will be seen that good agreement has been obtained.

It should be noted that for narrow sections, the most ductile material in bending is that with the highest local elongation. For wide sections, a low proof stress and a high rate of work hardening, particularly near failure are required in addition to high local elongation. In the case of extrusions, the softest tempers are not always those with the greatest elongation. Thus, all heat treated alloys except BS1476/HE9 and some HE10 compositions (1 per cent silicon, ⅝ per cent magnesium, no manganese, chromium or copper) have a local elongation when artificially aged as great as or greater than that of the naturally aged material; also some alloys have a relatively low local elongation when freshly quenched after solution heat treatment.

TABLE 1.—*Quoted and Calculated Minimum-Bend Radii for 0.064 in. thick sheet*

Alloy	Quoted Value	Calculated Value
B.S.1470		
1C—0	Flat	Flat
—¼H	Flat	Flat
—½H	Flat	Flat
—¾H	Flat—½t	Flat
—H	½t	Flat—½t
N3—0	Flat	Flat
—¼H	Flat	Flat
—½H	Flat	½t
—¾H	½—1t	½t
H	1—1½t	1t
N4—0	Flat	Flat
—½H	½—1t	Flat
N5—0	Flat	Flat
—¼H	1t	Flat
N6—0	Flat	Flat
—¼H	1t	½t
H15—0	Flat	½t
—W	1½t	2t
—WP	2½t	5t
H20—0	Flat	Flat
—W	½—1½t	1t
—WP	1½—2t	1t

With all sections, there is a "pulling in" of material from the straight part adjacent to the bend, and this reduces the actual strain in the outer fiber below the geometrical value on bends of small angle. In bends of small radius the shift of the neutral axis towards the inner fiber increases the outer-fiber strain. There is also a size effect—small sections have a greater limiting outer fiber strain than large ones. Dorn *et al.*[9] has shown that the reasons for this are at least partly metallurgical—thin sheet has a finer grain size and greater zero gauge length elongation than thick sheet.

APPLICATION OF THE THEORY TO GROOVED SECTIONS

The reduction in ductility in bending which results from lateral restraint suggests that if the outer surface of a wide section were grooved longitudinally the separate elements would then be free to contract laterally, and ductility equal to that of narrow sections would be obtained. The grooves would have to be of sufficient depth to ensure that the plane strain ductility of the "core" would not be exceeded. This requires the groove depth to be a minimum of:

$$\frac{\text{beam depth}}{2} \times \frac{\left[\begin{array}{c}\text{simple tensile local}\\ \text{ductility (per cent.)}\end{array}\right] - \left[\begin{array}{c}\text{plane strain local}\\ \text{ductility (per cent.)}\end{array}\right]}{\text{simple tensile local ductility (per cent.)}}$$

Grooves are not necessary on the compression side of the bend as the compressive ductility is adequate. The use of grooves in the tension side only shifts the neutral axis towards the compression side because of the altered stress condition in the outer fiber and the removal of material. This has the effect of increasing the outer-fiber strain required of the material for a given bend radius, i.e., increasing the minimum-bend radius. In the worst case, however, the increase in outer-fiber strain is about 6 per cent, for grooves of negligible width, and 9 per cent for a total groove width of 10 per cent of the section width, so that provided the grooves are not too wide they need be on the tension side only and the minimum-bend radius of the wide section will be almost the same as a narrow one. Fig. 16 shows narrow and wide specimens of ½ in. thick H15WP plate (A and B) bent to the minimum bend radii. Specimen C is a similar piece of plate but has machined grooves, and the minimum-bend radius is now the same as for the narrow specimen.

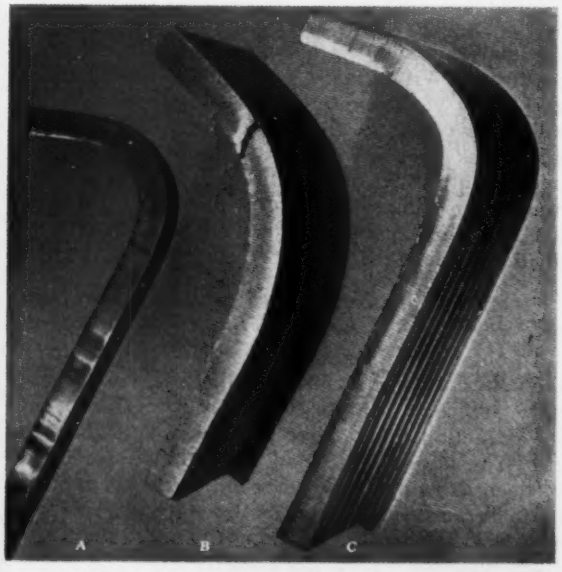


Figure 16. Minimum-bend radii of, from left to right, A narrow, B wide, and C grooved plate (½ in. thick H15WP).

In practical applications of this principle, a grooved or fluted section could be used where severe bends are required and where transverse stresses in service are small. A section of this type has already been used for aluminum alloy benk bars (mine roof supports)[12, 13] which are subjected to repeated plastic bending and straightening in service. The minimum-bend radius of the benk bars is not important, but the increased ductility gives them a longer life. Longitudinal grooves are used in these bars for other reasons, but it is probable that the effect demonstrated here has been a factor contributing to their satisfactory mechanical performance. Similar considerations doubtless apply to conventional steel benk bars, which are of a troughed or corrugated section.

SECTION IV: DEEP DRAWING

Single-stage deep drawing consists in pulling a sheet blank through a die by means of a flat-bottomed punch, the metal being allowed to move freely into the die but not to wrinkle, so that the finished shape is formed chiefly by compression of the periphery of the blank (Fig. 17). The cup can be redrawn if necessary in a similar manner, to give a deeper cup of smaller cross section.

In deep drawing, if the blank is thick, little or no wrinkling occurs, and a conical die is often used so as to suppress further any tendency to wrinkle; if it is thin, wrinkling is generally prevented by a spring- or pneumatically-loaded blank holder or pressure plate. The blank holder pressure should be just sufficient to obviate wrinkling—high loads put an additional load on the cup walls. Another method of preventing wrinkling is to use a fixed blank holder with a clearance of about 5 per cent, as in a double-acting press; this clearance prevents wrinkling yet is sufficient to allow thickening on thin shallow parts; thick deep parts require more clearance near the die throat, the amount depending on the rigidity of the tools.

Where there is insufficient radial clearance between punch and die to allow the thickened sheet to pass freely, ironing or thinning of the cup walls takes place. This will be considered in Section V. To avoid all ironing a radial clearance of up to 50 per cent of the original sheet thickness is needed, but the finished cup is then bell mouthed. This is avoided in practice by using a smaller clearance, say 30 per cent; still smaller clearances, 20 per cent

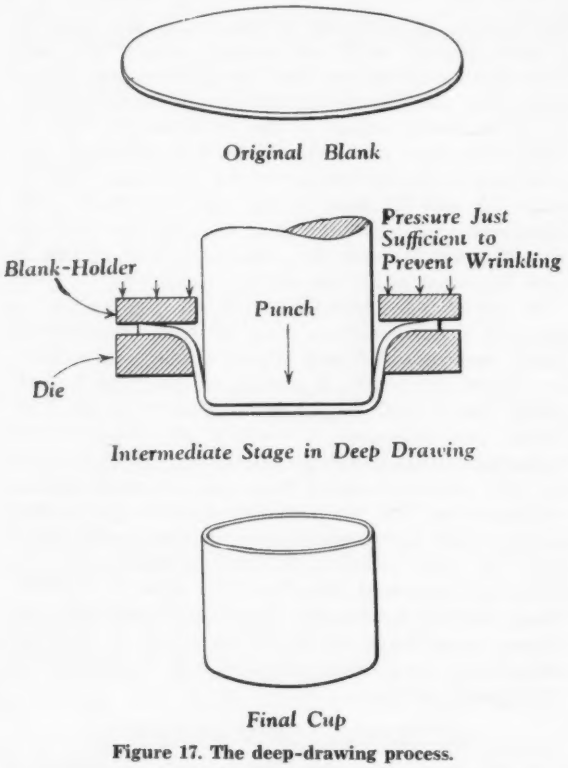


Figure 17. The deep-drawing process.

to 10 per cent, are often used to give a mild ironing action and produce a deeper cup of more uniform wall thickness. With this amount of ironing the additional load is not excessive and it occurs near the end of the stroke, where the drawing load is well past its peak, consequently the maximum reduction obtainable in deep drawing is not impaired. The minimum clearance that can be used without affecting the maximum reduction in deep drawing is around 5 per cent. In practice a clearance of 10 per cent on the nominal stock thickness is used to allow for the usual ± 5 per cent tolerance.

MODES OF FAILURE IN DEEP DRAWING

There are four ways in which failure in deep drawing can take place. In the first place, compression failure occurs in the form of a 45 deg. shear crack in the rim or flange of the cup, due to insufficient ductility of the material in simple compression (the rim is in substantially pure compression during drawing).

Secondly, tensile failure can take place high up in the wall of the cup, after the maximum load has been passed. The material near the top of the cup has to withstand a stretch of up to 60 per cent in the radial direction towards the end of the operation, under the action of the applied radial tension and induced circumferential compression. Because of this circumferential compressive stress the tensile ductility of the material in the radial direction is increased, so that materials with very little ordinary tensile elongation can withstand the necessary extension without failure, which only takes place in rather brittle materials, often when compression failure is imminent. This type of upper-wall tensile failure is not to be confused with tensile failures in ironing caused by attempting too great a reduction in wall thickness or by breakdown of the lubricant.

In the third place, a second type of tensile failure takes place at the neck in the wall near the junction with the bottom radius (punch-profile radius). This neck is produced by the plastic bending and straightening under tension which occurs as the sheet is pulled over the die-profile radius. The double flexure results in thinning in a region of the cup which receives very little other deformation, so that it appears as a neck. Further up the cup wall, this thinning, which occurs throughout the draw as the sheet is pulled over the die-profile radius, is masked by the considerable thickening which takes place as a result of circumferential compression. The severity of the necking depends upon the die-profile radius and the rate of work-hardening of the material. A die-profile radius of $10t_0$ is preferred (where t_0 is the original sheet thickness); beyond $10t_0$ there is little further advantage. With very large die-profile radii wrinkling is more difficult to control, because the area of sheet in contact with (and therefore controlled by) the blank holder is reduced; when the tendency to wrinkle is severe it may be necessary to use a very small die-profile radius.

In the fourth place, a third type of tensile failure and the most common mode of failure in deep drawing is that which occurs over the punch-profile radius, at the neck produced by plastic bending under tension as the sheet is formed to the punch profile. If other conditions are favorable for deep drawing, failure takes place in this region when too great a reduction is attempted. The optimum punch-profile radius is generally greater than $4t_0$, depending on the material and the punch-diameter: sheet-thickness ratio. With a very small punch-profile radius necking is very severe; with a large punch-profile radius (say, $10t_0$ to $20t_0$) considerable general thinning takes place as the sheet is stretch-formed to the punch contour. At intermediate curvatures the thinning is a minimum although it does not always follow that this condition will give the maximum reduction in deep drawing.

DESIRABLE CHARACTERISTICS OF MATERIALS FOR DEEP DRAWING

To obtain the deepest draws the requirements of the material are therefore as follows: Firstly it must have sufficient compressive ductility to withstand the reduction in diameter of the blank to form the cup. The largest reduction likely to be obtainable in deep drawing is 55 per cent., and this requires up to 55 per cent. contraction in length in a compression test. (Reduction in deep drawing is defined as $\frac{\text{Blank diameter} - \text{Mean cup diameter}}{\text{Blank diameter}}$ per cent.)

Secondly, it must have sufficient general elongation under combined stress to avoid upper-wall failure. In terms of elongation in simple tension this is small and failure generally occurs only in materials in which compression failure is imminent, so that if the first condition is satisfied the tensile ductility will probably be adequate.

Thirdly, it must have sufficient tensile ductility to withstanding bending under tension over the punch and die-profile radii without failure. If these radii are not too small or too large all alloys and tempers will withstand this.

Fourthly, the ultimate tensile stress should be high in relation to the compressive properties. The compressive properties determine the major portion of the load and the ability of the cup walls to take this load is determined approximately by the simple ultimate tensile stress.

It follows from these requirements that tensile ductility is no measure of deep drawability and is of importance only where punch and die-profile radii must be small, or the punch-profile radius very large. In fact, the very brittle materials generally fail in deep drawing for lack of compressive ductility. It should be added that tensile ductility gives little indication of compressive ductility; most alloys are far more ductile in compression than in tension, but much greater ductility in compression than in tension is called for in deep drawing. With regard to the fourth requirement, it does not follow that a soft material has any advantage over a hard one; in fact the reverse is usually the case—the hard alloys do not work-harden so rapidly in compression, so that although the compressive stresses of different tempers of an alloy are widely different at small deformations the relative differences become much less at large deformations.

CALCULATION OF DEEP-DRAWING PROPERTIES

A circular cup drawn from a circular blank is considered, being the simplest example of its type. The maximum reduction in deep drawing is that at which the maximum punch load developed during the drawing cycle is equal to the strength of the cup in tension. Chung and Swift [14] have calculated punch loads with very great accuracy, but the calculation even for one material is very lengthy. By using some of their results and a number of approximations however, it is possible to produce a fairly simple formula for punch loads giving sufficient accuracy for most purposes. The strength of the cup walls, on the other hand, can at present be calculated only approximately, and this is the most serious theoretical limitation. Practical difficulties are the determination of the true stress-strain curves for sheet in compression and the measurement of the coefficient of friction under deep-drawing conditions.

The total punch load includes that due to friction, the tension required to pull the sheet over the die-profile radius, and the major load imposed by the circumferential compression required to form the cup.

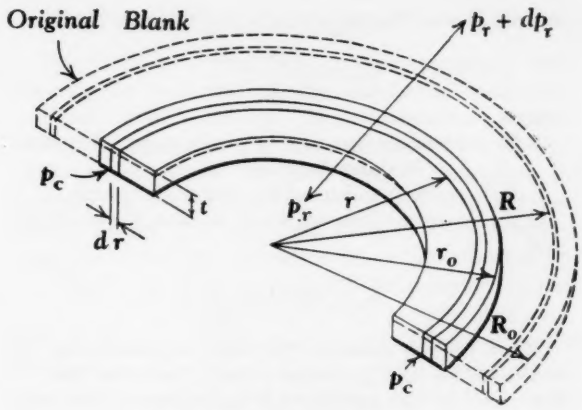


Figure 18. Plane radial drawing.

The latter depends on the work hardening of the material and the geometry of the cup. As drawing proceeds the load at first rises because of work-hardening but the amount of material being deformed is decreasing, so that the load reaches a maximum partway through the stroke.

Stress Due to Plane Radial Drawing.—Considering plane radial drawing only (Fig. 18), and ignoring friction and bending over the die-profile radius and stress in the "thickness" direction, it can be shown by equating forces on a particular element at any stage that

$$dp_r = -(p_c + p_r)\frac{dr}{r} - p_r\frac{dt}{t}$$

where

p_r = radial tension,
p_c = circumferential compression,
t = current thickness of the element,
and r = current radius of the element.

Although the blank thickens up considerably during drawing, the variation across the flange at any instant is less than 5 per cent., so that for obtaining the value of p_r at a given instant the thickness term, $-p_r\frac{dt}{t}$ can be ignored.

Von Mises' hypothesis for yielding in this case becomes

$$p_1^2 - p_1 p_3 + p_3^2 = f^2$$

where p_1 and p_3 are maximum and minimum principal stresses and f is the simple tensile (or compressive) yield stress. This equation is difficult to handle, so a straight-line relation, a modification of Tresca's maximum shear-stress criterion, is used, namely

$$p_1 - p_3 = 1.10\,f.$$

This is the best approximation to von Mises' curve, and although the maximum difference between this and von Mises' criterion could be up to 10 per cent., over the range of tension and compression in plane radial drawing, the difference is very small. Hence

$$dp_r = -1.10\,f\frac{dr}{r}.$$

The true radial tensile stress in the material at the

mean cup-wall diameter at any stage, p_{RP}, is thus

$$p_{RP}=1.10\int_{r_0}^{R_p} f\frac{dr}{r}$$

where

R_p = mean radius of cup walls ≏ punch radius + ½ sheet thickness

r_0 = current radius of the rim of the blank.

If the material does not work harden, f is constant and

$$p_{RP}=1.10\,f\log_e\frac{r_0}{R_p}.$$

When f is not constant, the above equation may be evaluated by taking a mean value f_m between that for the metal at the rim (which has received the least work) and that for the metal at the mean cup-wall radius at the considered instant (because this has received the greatest work in the early stages of the draw where the maximum load is reached). The equation may then be written

$$p_{RP}=1.10\,f_m\log_e\frac{r_0}{R_p}. \quad \ldots\ldots\ldots\ldots (1)$$

The quantities r_0 and R_p are known; it remains to evaluate f_m.

At any given instant, each element will have extended in the radial direction and compressed in the circumferential direction. Hill[15] has stated that the representative strain (the strain analogue of the root mean square shear stress) received by each element is directly proportional to the true circumferential strain, $\log_e\frac{R}{r}$, to within 3 per cent. for reductions in deep drawing of up to 50 per cent. where R is the original radius of the element. This means that the current yield stress of any element, whatever deformation it has experienced, corresponds to the circumferential strain received. At the considered instant, the circumferential strain of the rim is known; that of the element at the mean-cup-wall radius can be determined if its initial radius is known.

The original radius of the element at the mean cup-wall radius at any given instant is given by the following formula (derived from the constancy of volume of the element)

$$R=\sqrt{(r_0^2-R_p^2)\,\frac{t_m}{t_0}-R_0^2}$$

where t_0 = original blank thickness,

t_m = mean blank thickness at the considered stage,

R_0 = initial blank radius.

All the quantities in this expression are known except t_m. Chung and Swift[14] (Fig. 19) have calculated the thickness strains, due to plane radial drawing only, of materials with various strain hardening characteristics. If the values for t_m are taken from the average curve between that for a non-strain hardening

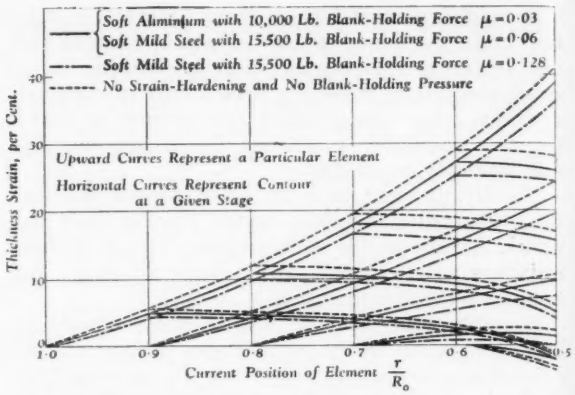


Figure 19. Development of thickness strain due to plane radial drawing (from Chung and Swift).

metal (which the harder tempers approach) and that for soft aluminum, the maximum error in the value of t_m for any aluminum alloy is ±1 per cent. At the point at which the maximum load occurs the error is a maximum of ±½ per cent. Thus t_m can be established with negligible error, and R can be evaluated. The radial strains of the rim and the element at the mean cup-wall radius at the considered stage can be calculated and the corresponding value of f_m obtained from the true stress-strain curve.

Stress due to bending and unbending over die radius

Chung[16] has shown that the radial stress p_B required to pull the sheet over the die profile radius, i.e. to bend or unbend it, using Tresca's yield criterion is given by

$$p_B \doteq \frac{f\,t}{4\,R_D}$$

where t = current sheet thickness,

f = yield stress,

R_D = radius to neutral axis of sheet ≏ die profile radius + ½ sheet thickness.

When von Mises' criterion is used this becomes

$$p_B=\frac{1.155\,f\,t}{4\,R_D}$$

For simplicity, the value of f for the material at the mean cup-wall radius, f_{RP}, can be taken for bending (this will tend to give slightly high results, as the metal at the beginning of the die-profile radius will have a slightly lower yield stress than that at the mean cup-wall radius). According to Chung and Swift's curves, at maximum load the value of t at the mean cup-wall radius is not much greater than the original blank thickness, and as the load due to bending and unbending is only about 10 per cent. of the total load errors in using t_0 will be small. Comparison with the more accurate (and more complex) formula of Chung and Swift[14] shows an error of about 3 per cent., which is negligible.

If R_D is 10 t_0, the formula becomes

$$p_B = \frac{1.155\, f_{RP}}{40} = 0.029\, f_{RP} \quad \ldots\ldots (2)$$

Stress Due to Blank Holder Load

The blank holder load H may be considered as being concentrated at the rim, because this is the thickest part of the flange. The radial tensile stress at the rim due to the blank holder load is $\frac{\mu H}{\pi r_0 t}$, where μ is the coefficient of friction. The radial tensile stress in the material at the mean cup-wall radius, p_{BF}, is given by

$$p_{BF} = \frac{\mu H}{\pi R_p t_{RP}}$$

where t_{RP} is the thickness at the mean cup-wall radius.

Since t_{RP} is not very different from t_0

$$p_{BF} = \frac{\mu H}{\pi R_p t_0} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

Stress Due to Friction

In computing the stress at the die radius, allowance must be made for the frictional component. The ordinary slow-speed transmission-belt design formula can be used here

$$T_1 = T_2\, e^{\theta \mu}$$

where T_1 = applied tension = p'_{TRP}

T_2 = back tension = $p_{RP} + p_{BF} + p_B$ (i.e., the sum of the stress due to plane radial drawing, the blank-holder stress, and the stress due to bending over the die radius)

θ = total angle of contact = $\pi/2$

whence

$$p'_{TRP} = e^{\mu \pi/2}[p_{RP} + p_{BF} + p_B]$$

$$= e^{\mu \pi/2}\left[1.10\, f_m \log_e \frac{r_0}{R_p} + \frac{\mu H}{\pi R_p t_0} + 0.029\, f_{RP}\right] \ldots\ldots (4)$$

Total Stress

After being drawn over the die radius the sheet is unbent to form the cup wall. To obtain the total stress the component due to unbending must be added to p'_{TRP}. The stress required to unbend the sheet is $0.029\, f_{RP}$, hence the total true stress in the material at the cup wall radius, p_{TRP}, is given by

$$p_{TRP} = e^{\mu \pi/2}\left(1.10\, f_m \log_e \frac{r_0}{R_p} + \frac{\mu H}{\pi R_p t_0}\right) + (e^{\mu \pi/2} + 1)\, 0.029\, f_{RP} \ldots\ldots (5)$$

p_w, the nominal stress (i.e., on original thickness) in the cup wall adjacent to the punch, is therefore

$$p_w = e^{\mu \pi/2}\left(1.10 \frac{t_m}{t_0} f_m \log_e \frac{r_0}{R_p} + \frac{\mu H}{\pi R_p t_0}\right) + (e^{\mu \pi/2} + 1)\, 0.029\, f_{RP} \ldots\ldots (6)$$

FORMING LIMITS

The limit of formability in deep drawing may usually be regarded as the maximum reduction without tensile failure. The calculation of the strength of the cup in tension requires a knowledge of the exact position at which failure takes place, in addition to the amount of work and thinning received by the cup walls and the friction conditions over the punch-profile radius. Moreover, the failing load and position of fracture will be uncertain in the early part of the draw, before the parallel walls are formed. For simplicity the strength of the cup walls is taken as the simple ultimate tensile stress of the unworked material, failure being assumed to take place in the walls near the junction with the punch-profile radius. To calculate the maximum percentage reduction obtainable in deep drawing, the stresses due to the punch loads are calculated for various stages of the drawing cycle for a given reduction, say 50 per cent, and the maximum stress for this reduction obtained. The calculations are repeated for other reductions until the maximum reduction at which the maximum stress does not exceed the ultimate tensile stress of the material can be obtained by interpolation.

This has been done for a number of alloys and values are compared with experimental results for fairly thick sheet (and consequently low blank holder pressure) in Table 2. (Lower results would be obtained with thinner sheet where blank holder pressures must be high.) It will be seen that although individual results do not always correspond closely, the theoretical and experimental values agree in general trend. First, the various tempers of the H20 alloy are all shown to have very similar "drawability" in spite of widely different mechanical properties. Also, the improvement in deep drawability on cold working of NS3 alloy is clearly revealed. Better agreement might be obtained if more accurate values for cup-wall strength and coefficient of friction were available. For the less ductile alloys, H15W and H15WP, values are given for the maximum reduction possible without tensile failure, although the cups cracked in the rim in compression early in the draw.

The accuracy required of the forming limits for practical purposes is about 10 per cent, because a safety factor of this order must be applied to cover variations in material, etc. In deep drawing the practical value of a shell is measured by its height in relation to its diameter rather than by the percentage reduction from the original blank. An accuracy of 10 per cent of the cup height is therefore required. A small variation in reduction from the blank, however, gives a large alteration in cup height, and in terms of drawing reduction, and thus

TABLE 2.—*Calculated and Experimental Values for Maximum Reduction in Deep Drawing*

Alloy	Maximum Reduction in Deep Drawing $= \frac{\text{(Blank Diameter-Mean Cup Diameter)}}{\text{Blank Diameter}}$ per cent.		Approximate $\frac{\text{Cup Height}}{\text{Cup Diameter}}$ ratio calculated from Blank Diameters	
	Calculated	Experimental	Calculated	Experimental
B.S.1470				
1C—0	49.8	50.0	0.74	0.75
N3—0	48.6	46.7	0.69	0.63
—¾H	51.9	48.7	0.83	0.70
N5—0	53.2	54.3	0.89	0.94
H20—0	48.3	51.5	0.69	0.81
—FW (Freshly Quenched)	48.1	51.5	0.68	0.81
—W	47.5	51.5	0.66	0.81
—WP	47.6	51.5	0.66	0.81
H15—W	47.3	48.7 (rim cracked at 36)	0.65	0.70
—WP	47.0	48.7 (rim cracked at 42)	0.64	0.70

of forming loads and cup-wall strength, an accuracy of about 3 per cent is necessary.This makes the reliable calculation of deep drawing properties very difficult, quite apart from the complexity of the process itself. The range of values obtained in the present study is from 47 to 54 per cent; although the range appears to be a narrow one, at 54 per cent reduction the cup is nearly 50 per cent higher than at 47 per cent reduction for a given cup diameter. A reduction of 50 per cent in deep drawing is very good, but 40 per cent would be considered rather poor and 20 per cent would be useless for cups as it represents a mere turning up of the edge of the blank.

BLANK HOLDER LOAD AND FRICTION

The blank holder load ranges from zero for thick blanks up to several times the punch load for large diameter blanks in thin sheets, and is roughly proportional to $\left(\frac{R_0 - R_p}{t_0}\right)^2$. With a blank holder load of five times the failing load of the cup and a coefficient of friction of 0.1, the stress in the cup wall due to the blank holder load is $0.1 \times 5 \times$ ultimate tensile stress; i.e., the blank holder friction takes up half the drawing load and any variation in the coefficient of friction will make a great difference to the drawability. From a limited number of tests it seems that, for a given set of conditions, although the stronger the material the greater must be the blank holder load, the ratio of blank holder load to the failing load of the cup may be less for the stronger material, which is therefore at an advantage. This is because the wrinkling tendency depends not only on the yield stress, but also on the plastic modulus or slope of the stress-strain curve in the plastic range, so that although the soft materials have a lower proof stress the stress-strain curve in the plastic range is steeper.

It is frequently observed in practice when drawing thin blanks, using a pressure-loaded blank holder, that wrinkling occurs when the quantity of lubricant is excessive. It is suggested that the explanation of this is a purely mechanical one and is not due to any change in friction conditions. With a thick lubricant film, the blank holder is given a clearance in effect, which may allow the blank to wrinkle. A few tests showed that with a normally oily blank, the oil film did not exceed a few ten-thousandths of an inch in thickness, but when too much oil was obviously present the film thickness was as great as 0.0025 in., giving a blank holder clearance of 0.005 in. —enough to allow wrinkling on quite thick (0.036 in.) blanks. The oil film between two parallel surfaces is not rapidly squeezed out even under considerable normal pressure, consequently once an excess of oil has been applied it will tend to persist during plane radial drawing (when the blank is liable to wrinkle), especially in high speed presses where there is little time for the oil to be expelled.

OTHER APPLICATIONS

The method of calculation described here could perhaps be applied to allied operations such as the re-drawing of cups. However, there are at least three different methods of re-drawing and it can be done with or without intermediate annealing; there are also certain difficulties not present in single-stage drawing, such as the variation in thickness of the cup before re-drawing.

The method might also be applied to the drawing of rectangular shells, but a few calculations have shown that modification would be necessary. It might be thought that the four corners could be considered as constituting a circular cup, the straight sides being subjected only to bending and straightening under tension. Calculations on this basis, however, yielded low values for the maximum reduction, no doubt due to the fact that in practice some of the material from the corners is not completely compressed, as in a circular cup, but "crowds" into the straight sides. As the amount of compression is then reduced,

the loads are lower, giving a greater maximum reduction than would otherwise be expected. This crowding in, which is analogous to the pulling in of material from the straight part adjacent to the radius in bending operations, would be very difficult to allow for in calculation.

SECTION V: IRONING

This consists of reducing the wall thickness of a shell by pulling it through a die (Fig. 20) and is analogous to wire drawing. The process is used for parts requiring a thick base with thin walls, as, for example, cartridge cases. The ironing may be carried out as a single operation, or may be combined with simultaneous deep drawing, either as a small degree of corrective ironing or as a large reduction in ironing combined with a small amount of re-drawing. By using a long-stroke press, a blank can be deep drawn and subjected to several ironing reductions at one operation, as in the Keller press.[17]

The chief practical difficulty in ironing is the maintenance of a lubricant film between shell and die, for the pressures involved are very high, higher than in deep drawing. The optimum shape for the die is generally agreed to be conical, with little or no edge radius; if the edge radius is an appreciable proportion of the reduction in wall thickness the local pressures generated may lead to breakdown of the lubricant, with build-up on the die, giving scoring and eventual failure of the shells. Swift[18,19] has shown that for small reductions a small die angle gives the lowest punch loads, and for large reductions a large die angle gives the lowest loads. A suitable angle for most purposes is 10-15 deg.; when the wall thickness is very great it may be necessary to increase the die angle to 20 or 30 deg. to avoid the inconvenience of having to use very deep dies. The finish obtainable depends on the die finish and on the lubricant. At normal press speeds a relatively thick hydro-dynamic lubricant film can be formed provided the lubricant is very viscous so that it is not readily squeezed out from between the shell and the die; a typical matt finish with the least coefficient of friction is then obtained. The usual lubricants, however, are of too low a viscosity for a thick lubricant film to be maintained, and only a thin film forms, so that the die finish now has a considerable effect on the surface of the shell, and if a polished die is used a bright burnished shell is obtained. Thin-film conditions are somewhat critical, as the film easily breaks down leading to scoring. Lubrication conditions between shell and punch are much less severe, consequently thick-film lubrication is normally obtained on the inside of the shell, accompanied by a matt finish.

Other practical difficulties occur when the punch is long and slender, as in the Keller press. Near the end of the stroke, bending of the punch may occur because of the uneven height of the shell, leading perhaps to fouling of the punch and die. The thickness near the rim of the shell is then uneven, due to the bending of the punch, and in a subsequent ironing pass slivers of thicker material from the rim may break off; these may lodge on or between the die rings and cause failure of subsequent shells, and perhaps fouling of the tools.

If the die angle is large, the reduction small and the shell wall thick, a "wave" of material forms immediately ahead of the die ring, due no doubt to longitudinal compressive stress at this point; in extreme cases the wave height may be as great as four times the depth of ironing reduction (Fig. 21). Under the opposite conditions, i.e. with a small die angle, thin walls and a heavy reduction, a slight depression appears in front of the die ring. These phenomena complicate any attempt to calculate ironing loads and ductilities; however, the depression is generally insufficient to affect results seriously, and since the ironing wave occurs only at small reductions it is not present at the limiting reductions which are considered here.

For ductile alloys the maximum reduction in wall thickness possible in a single ironing pass is that at which the tensile stress in the already ironed walls, due to the ironing load, reaches the yield or ultimate stress of the material. Since the yield and ultimate stress are very close, as a result of the severe cold working, it is convenient and safer to take the yield stress—indeed it is hardly practicable to work above this stress. Where a number of ironing reductions are being made in one stroke, as in the Keller press, the

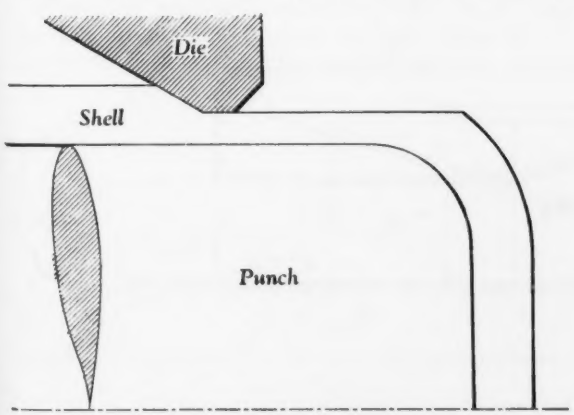


Figure 20. The ironing process.

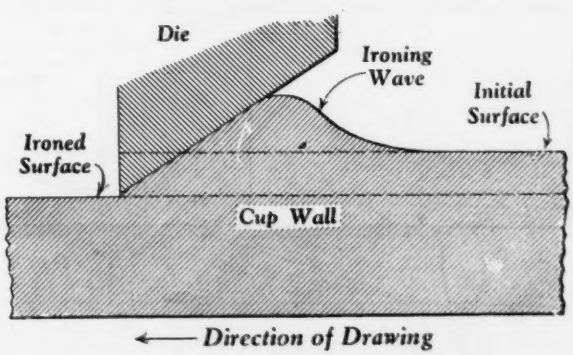


Figure 21. Formation of ironing wave (after Swift).

maximum reduction obtainable at each die ring will depend on whether one pass is complete before the next one is commenced, or whether the shell is in two ironing rings simultaneously during part of the stroke. With the less ductile alloys, if too great a reduction is attempted failure will take place as a longitudinal split in the material undergoing ironing owing to exhaustion of ductility under combined stress. In this respect ironing is similar to deep drawing—failures may occur either from lack of ductility or the inability of the shell walls to withstand the load. As the weakest part of an ironed shell is in the (parallel) ironed walls the failure strength can be easily established, unlike deep drawing where tensile failure may occur at some point over the punch-profile radius. Swift [18,19] has calculated punch loads in ironing with reasonable accuracy for circular shells with a maximum wall thickness of one-quarter of the punch radius. He has shown that the total punch load consists of two parts, the load in the shell walls and the load carried as traction by the punch as a result of friction between shell and punch. In order to keep the stress in the shell walls at a minimum the friction between shell and punch should therefore be as high as possible and that between shell and die as low as possible. In practice lubrication conditions are far from this ideal.

CALCULATION OF IRONING LOADS

Thin-walled Shells

Thin-walled shells, where the thickness is less than, say, $\frac{1}{16}$ of the punch radius, will be considered first. Fig. 22 shows Swift's assumed stress system for an elementary strip of such a shell perpendicular to the axis of ironing. In fact, the distortion of an element is accompanied by considerable shear, but this will be allowed for later. Since the metal moves forward along the surface of the die, the frictional stress $\mu_1 p_3$ on the outer surface of the elementary strip is in the reverse direction, as shown. On the other hand, since the punch moves forward at the same speed as the fully ironed material, and therefore faster than the metal in the die, the frictional stress $\mu_2 p_3$ on the surface of the strip is in the forward direction. The stress distribution shown is only approximate; the axial stress p_1, for example, cannot be a principal stress, but is associated with a non-uniform shear stress, and varies in intensity from the outer to the inner surface of the wall. Nor in general will the radial stress p_3 have the same value on both surfaces, but as Swift obtained good agreement between calculated and measured punch loads, the approximations are considered justified. Using the notation of the figure, equating forces on the element, and neglecting changes in mean radius during ironing

$$h\frac{dp_1}{dx} - p_1 \tan\alpha = p_3(\tan\alpha + \mu_1 - \mu_2)$$

giving

$$\frac{dx}{x_0 - x} = \frac{dp_1}{p_1 + p_3 + p_3\left(\frac{\mu_1 - \mu_2}{\tan\alpha}\right)}.$$

In a thin-walled shell the circumferential strain can be ignored, hence the material is in plane strain and the circumferential stress $p_2 = \frac{p_1 - p_3}{2}$.

Using von Mises' yield criterion, the yield condition is

$$p_1 + p_3 = 1.155 f_1$$

where f_1 is the mean simple tensile (or compressive) yield stress of the material during ironing proper.

Hence

$$\frac{dx}{x_0 - x} = \frac{dp_1}{1.155 f_1 + (1.155 f_1 - p_1)\left(\frac{\mu_1 - \mu_2}{\tan\alpha}\right)}$$

and integrating this, the stress at exit from the die is shown to be

$$p_{1A} = 1.155 f_1\left(1 + \frac{\tan\alpha}{\mu_1 - \mu_2}\right)\left(1 - \sqrt{\frac{x_0 - x_1}{x_0}}^{\frac{\tan\alpha}{\mu_1 - \mu_2}}\right).$$

Shear at entry and discharge

In addition to the "pure" ironing or actual useful

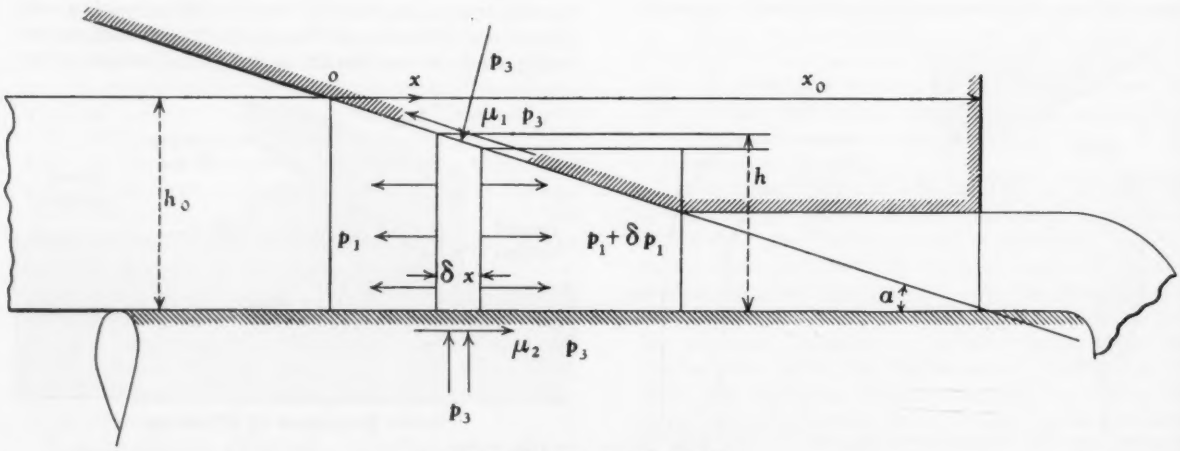


Figure 22. Ironing (after Swift).

work in reduction of wall thickness, there is a shear distortion at entry and exit, as shown in Figure 23. The element will be considered to shear instantaneously at entry, undergo ironing proper and then shear at the moment of exit.

The work done in shear per unit volume $= s_0 \tan \theta$ where s_0 is the mean shear yield stress of the material at entry, and θ is the angle through which the element is sheared.

Work done on a length δx of the cup wall

$$\delta W_0 = \int_0^{h_0} s_0 \tan \theta \, \delta x \, 2\pi r dh$$
$$= \pi r h_0 \, \delta x \, s_0 \tan \alpha.$$

This is the work which must be done in the ironed wall by an additional drawing force, F, whence

$$F \, \delta x \frac{h_0}{h_1} = \delta W_0$$

The corresponding mean stress in the ironed walls due to this shearing is therefore $p_{s0} = \frac{s_0 \tan \alpha}{2}$. Similarly, the corresponding mean stress required to undistort the metal at exit, $p_{s2} = \frac{s_2 \tan \alpha}{2}$, where s_2 is the mean shear yield stress of the material at exit. On a material in pure shear (balanced tension and compression) there is no stress or strain in the third direction. Using von Mises' yield criterion, therefore,

$$s_0 = \frac{f_0}{\sqrt{3}} \text{ and } s_2 = \frac{f_2}{\sqrt{3}}.$$

Total Stress

From the foregoing the total mean tensile stress in the ironed walls, p_T, is given by

$$p_T = \frac{f_0 \tan \alpha}{2\sqrt{3}} + 1.155 f_1 \left(1 + \frac{\tan \alpha}{\mu_1 - \mu_2}\right)$$
$$\left(1 - \frac{\tan \alpha}{\mu_1 - \mu_2} \sqrt{\frac{x_0 - x_1}{x_0}}\right) + \frac{f_2 \tan \alpha}{2\sqrt{3}}.$$

For each reduction calculated, the mean yield stresses are determined from the area under the appropriate part of the true-stress/true-strain curve. The quantity f_0 is evaluated between strains of 0 and $\left[\frac{\tan \alpha}{\sqrt{3}}\right]$ (the equivalent strain in simple tension or compression), f_1 between $\left[\frac{\tan \alpha}{\sqrt{3}}\right]$ and $\left[\frac{\tan \alpha}{\sqrt{3}} + 1.155 \log_e \frac{h_0}{h_1}\right]$ and f_2 between $\left[\frac{\tan \alpha}{\sqrt{3}} + 1.155 \log_e \frac{h_0}{h_1}\right]$ and $\left[\frac{2 \tan \alpha}{\sqrt{3}} + 1.155 \log_e \frac{h_0}{h_1}\right]$.

Forming Limits

The yield stress of the ironed walls is influenced by the prevention of circumferential strain by the support given by the punch. Using von Mises' yield criterion, the mean yield stress of the walls is $1.155 f_3$, where f_3 is the mean simple tensile or compressive yield stress of the material at exit; this is the stress corresponding to a strain of $\left[\frac{2 \tan \alpha}{\sqrt{3}} + 1.155 \log_e \frac{h_0}{h_1}\right]$.

The maximum reduction at which p_T does not exceed $1.155 f_3$ can thus be calculated for a given die angle, if the coefficients of friction are known. In the present case, values were taken from Bland, Whitton and Ford's[20,21,22] back-tension rolling results, in which the back tension in rolling was increased until the rolls were about to skid on the strip. The method has the advantage that the coefficient of friction is measured during actual deformation, and the only assumption is that there is no lateral spread of the material, which is true if it is fairly wide. A mean coefficient of friction is obtained over the arc of contact, as is required for rolling theory. The relative speed between strip and rolls under these conditions varies between zero and a relatively small maximum; in ironing, although the type of deformation is not entirely dissimilar, the relative speed between shell and die (although probably not between shell and punch) is higher, and this might be expected to give slightly lower values of coefficient of friction than those obtained in rolling. However, these are the best values available for coefficients of friction under bulk plastic deformation. Values obtained by Ford *et al.* for thin-film lubrication (burnished surface), which

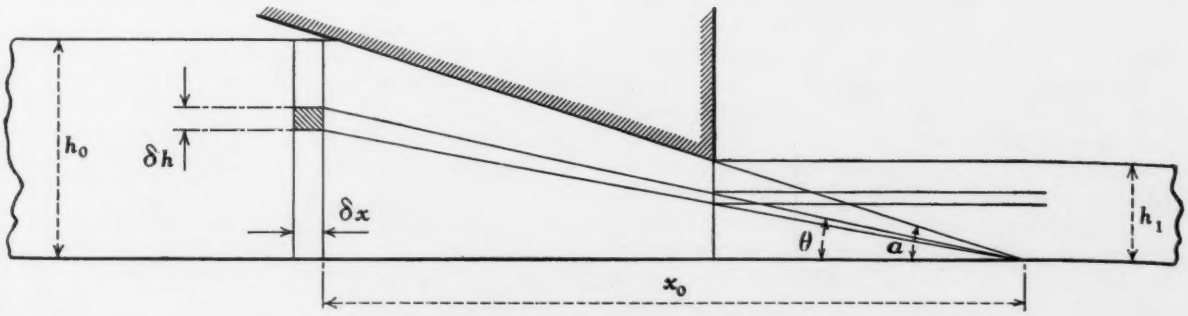


Figure 23. Shear at entry and discharge (after Swift).

usually exists between shell and die, ranged from 0.06 to 0.08; for thick-film lubrication (matt surface), as is usual between shell and punch, values ranged from 0.03 to 0.05. In the present study, for average conditions $\mu_1 = 0.07$ and $\mu_2 = 0.04$ were taken; for the worst case (without actual breakdown of die-shell lubrication) $\mu_1 = 0.08$ and $\mu_2 = 0.03$ were adopted. The best condition likely to be met with in practice is that of thick film lubrication between shell and die, with $\mu_1 = \mu_2$. Maximum reductions in ironing have been calculated for these three conditions for various aluminum alloys, for a 15 deg. die. The results are given in Table 3. It will be seen that the differences between the three friction conditions are not very great, so that if the coefficients are not very accurate the calculated maximum reduction will not be much affected.

TABLE 3—*Calculated Values of Maximum Reduction in wall thickness obtainable in Ironing without Tensile Failure*

Semi-die angle 15 deg. μ_1 = coefficient of friction between shell and die. μ_2 = coefficient of friction between shell and punch.

Alloy	Thin-walled cups. Reduction per cent.			Trick-walled cups Reduction per cent.
	Best Case $\mu1 = \mu2$	Intermediate Case $\mu1 = .07$, $\mu2 = .04$	Worst Case $\mu1 = .08$ $\mu2 = .03$	Orig. wall thickness / Punch radius $< \frac{1}{4}$ $\mu1 = .07$ $\mu2 = 0$
B.S.1470				
1C—0	63	61	60	56
N3—0	59	57	57	52
—¾H	58	57	55	51
N4—0	58	57	55	51
N5—0	59	56	55	51
H20—0	58	57	56	52
—FW (Freshly quenched)	59	57	56	52
—W	56	54	52	48
—WP	56	54	53	47

It will be noted that the differences between the alloys are small. This is to be expected because the ability of the ironed walls to withstand the ironing loads does not vary much for different materials; it depends only on the shape of the true-stress/true-strain curve at large strains. Slightly higher values are obtained on the alloys with the higher rates of work hardening at high strains, such that f_3 (determining the ability of the ironed walls to take the load) is high compared with f_1 (determining the major portion of the load). Large differences in the shape of stress-strain curves for different alloys occur only in the initial part of the curve, and since the reductions considered here extend considerably beyond the initial knee of the curve, the differences so apparent between the $\frac{\text{Proof Stress}}{\text{U.T.S.}}$ ratios, for example, are of little importance. Likewise, the effect of prior cold work is small (compare NS-O and NS3-¾H) provided only that the material has sufficient ductility remaining to avoid longitudinal splitting. For multiple ironing passes, therefore, the maximum percentage reduction (on the wall thickness from the previous pass) for all passes will be very similar, and failure will finally take place when the fracture ductility under the particular stress conditions is exhausted.

Unlike deep drawing, there is no advantage in reducing the percentage reduction at each subsequent pass, as is often done in ironing. (The percentage reduction on the original wall thickness at each pass will, of course, decrease.) The differences between the various alloys—again in contrast to deep drawing—are probably too small to be made use of in practice, as the difference between, say 56 per cent. and 63 per cent. reduction in the wall thickness of a thin shell is only a few ten-thousandths of an inch. It would be hardly practicable or necessary to work to these limits, especially as variations in thickness of original stock, elastic expansion of die rings, etc., would be much greater than this. The shell height is almost exactly proportional to the percentage reduction, so that an accuracy of, say, 10 per cent. in the value for the maximum reduction is sufficient.

A few practical tests were carried out to check the calculated values of maximum reduction. The maximum reduction obtained on thin-walled shells in S1C-O alloy was 61 per cent., comparing well with values derived from theory; H9-W, the only other material on which results were available, gave a maximum reduction of 52 per cent. This is slightly lower than would be expected, but lubrication was not satisfactory, as there was slight scoring on the shell wall.

THICK-WALLED SHELLS

Swift has adapted the previous formulae for ironing loads for use with thick-walled shells, and obtained good agreement between calculated and measured punch loads for shells up to a wall thickness of one-quarter of the punch radius $\left(\frac{h_0}{r_1} = \frac{1}{4}\right)$. Using the notation in Figs. 22 and 24, the equation for equilibrium of an element is

$$r\,h\frac{dp_1}{dx} = (p_1 + p_3)r_x \tan\alpha + p_3(\mu_1 r_x - \mu_2 r_1)$$

where $r = \frac{r_x + r_1}{2}$.

As the material is not in plane strain the yield con-

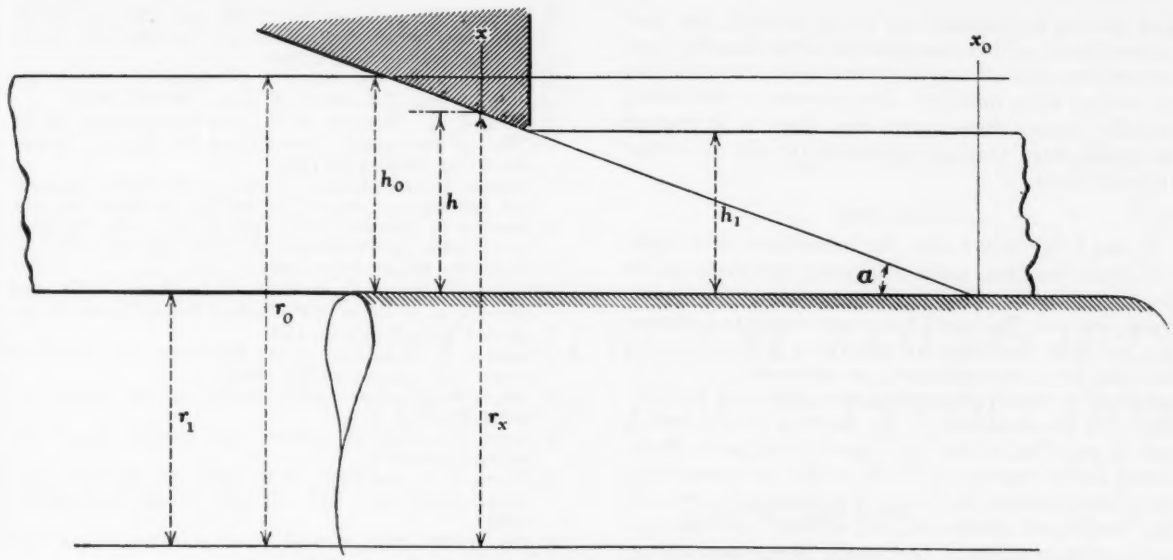


Figure 24. Notation of ironing of thick-walled cups (after Swift).

dition (using von Mises' criterion) will vary with the amount of reduction and will lie between

$$p_1+p_3=1.0\,f \text{ and } 1.155\,f, \text{ near to } 1.155\,f.$$

Accordingly, $1.155\,f$ is taken, giving a slight underestimate for maximum reduction.

Hence

$$r\,h\frac{dp_1}{dx}=1.155\,f_1\,r_x\tan\alpha+(1.155\,f_1-p_1)(\mu_1\,r_x-\mu_2\,r_1)$$

This equation is not readily solved unless $\mu_1 r_x = \mu_2 r_1$, or $\mu_2 = 0$. The first condition is unlikely as it means that friction between shell and punch is greater than that between shell and die; the second case is more nearly correct, as it means no friction between shell and punch, the cup taking the whole of the punch load. This is obviously not so, but the friction is probably less than with a thin-walled cup, and in any event with this assumption the values for maximum reduction obtained will be slightly on the conservative side. Hence

$$p_{1A}=1.155\,f_1\left(\frac{\tan\alpha}{\mu_1}+1\right)\left[1+\left(\frac{r_A^2-r_1^2}{r_0^2-r_1^2}\right)^{\frac{\mu_1}{\tan\alpha}}\right].$$

Shear at entry and exit is calculated on the same basis as for thin-walled cups, and

$$p_{s0}=\frac{f_0\tan\alpha\left(\frac{r_1}{2}+\frac{h_0}{3}\right)}{\sqrt{3}\left(r_1+\frac{h_1}{2}\right)} \text{ and } p_{s2}=\frac{f_2\tan\alpha\left(\frac{r_1}{2}+\frac{h_1}{3}\right)}{\sqrt{3}\left(r_1+\frac{h_1}{2}\right)}.$$

The total stress is the sum of p_{1A}, ps_0 and ps_2, as before.

Values of maximum reduction have been calculated for the various alloys for a 15 deg. die angle and a coefficient of friction $\mu_1=0.07$, and are given in Table 3. It will be seen that reductions are a little lower than for thin-walled cups.

DUCTILITY IN IRONING

A knowledge of the fracture ductility in ironing would allow the maximum reduction to be calculated for alloys the ductility of which is exceeded in the first pass before tensile failure takes place, and would also enable the maximum total reduction in multiple ironing passes to be calculated for the more ductile alloys, which eventually fail owing to exhaustion of fracture ductility.

The fracture ductility of a material in ironing can be calculated along the lines used by Dorn for calculating ductilities in bending, if the yield and fracture criteria are known for the particular stress conditions. For a material to just fail in ironing, fracture will occur at the end of the operation, i.e., at the completion of the final shear. In pure shear, as in thin-walled cups (i.e., balanced tension and compression, with no circumferential stress) the yield and fracture criteria are known, and it is found for some alloys, which are known to fail in ironing by lack of strength and not lack of ductility, that in theory they have insufficient ductility to undergo the two shearing operations, apart from ironing proper. This anomaly is due to the simplifications adopted in assuming that the shearing was instantaneous and separate from the ironing proper, whereas, in fact, the shearing doubtless occurs over a finite distance inside the ironing ring, when the presence of additional compression increases the ductility. For calculating ironing loads and therefore maximum ironing reductions of ductile alloys, the original assumptions are satisfactory, because the shearing loads are only a small proportion of the total ironing load where reductions are large

and friction appreciable, as in the limiting case considered here, so that inaccuracies in the shearing load are not important. Even if a more exact stress analysis of ironing were made for the purpose of calculating ductility under these conditions, there is at present no satisfactory fracture criterion for metals under triaxial stress.

CONCLUSIONS

It has been shown that the formability of a material under the chief types of forming operation can be predicted with sufficient accuracy from the stress-strain curves. The need for more accurate information on yield and fracture criteria of different alloys has also been demonstrated. A more accurate calculation of cup-wall strength in deep drawing is desirable and an extension of the method to re-drawing and, if possible, to the drawing of rectangular shells. Other lesser operations which might be amenable to calculation are the shrinking of cylindrical parts, and the bending of tubes with and without internal supports of various kinds. Eventually it is hoped to present the results obtained here in tabular form for use by designers and others.

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Westinghouse Electric Corporation will provide the nuclear propulsion equipment for a nuclear powered guided missile light cruiser (CLGN), included in the 1957 Shipbuilding Program. The ship will be built by Bethlehem's Quincy Yard.

"JOURNAL INSTITUTE OF METALS"

METALLURGICAL RESEARCH IN NUCLEAR POWER PRODUCTION

ACKNOWLEDGEMENT

J. G. Ball, of the Metallurgy Division, Atomic Energy Research Establishment, Harwell, is the author of this paper, which was printed in the March, 1956, edition of "The Journal of the Institute of Metals."

INTRODUCTION

THE PART which metallurgical research will play in the development of nuclear energy is indicated by a broad review of some current and future problems, but no attempt has been made to treat any of the subjects in great detail. The special techniques demanded by the toxicity of materials such as plutonium and beryllium are not discussed because, although they reduce the rate of work in the laboratory, they do not significantly affect the metallurgical science of the investigations. For the same reasons no reference is made to the techniques used for handling gamma-active specimens after pile irradiation.

METALS AND NUCLEAR ENERGY

1. GENERAL

Many of the problems with which metallurgists have so far had to deal in the development of nuclear energy have arisen because of the peculiar behavior of metallic nuclear fuels. Until recently the fuel of nearly every reactor constructed has been uranium metal. Uranium is a highly reactive metal of complex structure (in its α and β forms) and new problems were created when it was set to work in reactors operating at a temperature where oxidation was rapid, where there were high neutron fluxes, and where the temperature varied in an irregular fashion. In the early stages, the metallurgist's problem was to produce the metal suitably protected and in a satisfactory structural condition to withstand periods of several months in the reactor without failure. The purpose of the early reactors built during the war was to produce plutonium for military purposes, and, as soon as it became available in sufficient quantities, the metallurgical properties of that metal had to be investigated.

More recent developments have enlarged the field of work to the point where success or failure of a reactor project depends upon the satisfactory solution of metallurgical problems. For power production, the nuclear fuel must be able to withstand much higher neutron doses than in the early plutonium-producing piles. As will be seen later, unalloyed uranium is unlikely to prove satisfactory for such reactors, and the metallurgist must investigate alloy structure and mechanical and physical characteristics in relation to irradiation behavior.

In the quest for economic power, high heat ratings (the usual units are megawatts per tonne of fuel) are of great importance, and new metallurgical problems arise with the introduction of better methods of heat removal. High-pressure water and sodium are examples of heat-transfer media which will be important in the next phase of power development. In both instances problems of corrosion have to be solved, and mechanisms are involved which are only imperfectly understood.

The new types of reactor operating at high ratings call for a wide variety of sheathing materials, and both the chemical and physical interactions of these with the fuel have been extensively investigated. The use of new materials has also called for work on their fabrication and joining characteristics.

This type of problem has arisen from the need to build power reactors, but much work of a fundamental kind has also been carried out with the ob-

ject of providing a background against which future development can take place with less empiricism than would otherwise be the case. For example, the general alloying behavior of the heavy elements has been investigated in a way which has not only provided the equilibrium diagrams of alloys of technological importance, but has also given some insight into the general principles of solid-solution and compound formation. Irradiation damage in non-fissile materials has been investigated as a fundamental problem in solid-state physics, work being done on order-disorder changes, precipitation from supersaturated solid solutions, and changes in mechanical properties. It is not yet clear whether the effects in constructional metals will prove of technological significance in power reactors.

Nuclear energy has produced a new tool for metallurgical work in the form of neutron diffraction (which has been used particularly on the problem of anti-ferromagnetism) and active tracer methods.

2. METALS OF INTEREST

The metallurgist engaged in nuclear-energy research probably has to consider, at some time or another, most of the commercial metals and alloys, but his work is concerned chiefly with materials which have been little studied in the past. These metals and their alloys can be grouped according to their functions (Table I).

With few exceptions these metals cannot be used unalloyed, because of the special properties required.

TYPES OF REACTOR AND THEIR SPECIAL PROBLEMS

The primary classification of reactors is broadly by the average energy of the neutrons causing fission. Thus, thermal reactors possess low-energy neutrons (average energy about 0.5 MeV., but when fully thermalized after moderation about 0.025 eV.) and fast reactors possess high-energy neutrons (about 2 MeV.). Not much is yet known about intermediate reactors, and present indications are that neutron gain factors would be prohibitively low. The power program is therefore likely for some time to be limited to fast and thermal reactors. While it is not relevant to discuss in detail the working of these reactors, some of their features influence the associated metallurgical problems. For example, there must not be much moderation in a fast reactor, so that light elements, which would greatly reduce the energy of the neutrons, must be avoided. The core will be small and in present reactors consists of relatively concentrated fissile material. A high rate of irradiation must be achieved if these reactors are to be economical, and one of the main problems facing the metallurgist at present is the production of a concentrated fuel capable of a high burn-up* without failure, so that the number of times the fuel must be chemically processed and reconstituted is kept to a minimum.† In a thermal reactor the concentration of fissile atoms is usually much lower than in a fast reactor and, if enrichment‡ is possible, alloys dilute in the fissile metal can be contemplated. This gives a much greater freedom in obtaining a given type of desirable metallurgical structure. Further sub-divisions arise, since the fuel may be solid or liquid and, in the latter case, it may be used as the reactor coolant.

Three general types of thermal reactor could be used for power production and the metallurgical work will center around the coolant and the fuel elements. The reactors are listed below with some comments on their characteristics.

TABLE I.—*Metals for Use in Nuclear-Energy Work.*

Metals	Comments
Uranium Plutonium Thorium	Fissile or fertile metals.
Aluminum Magnesium Zirconium Beryllium	Metals with low capture cross-section for thermal neutrons: used as canning materials for thermal reactors, choice being decided by temperature of operation, corrosive environment, and other factors. Beryllium is also used as a moderator.
Niobium Molybdenum Tantalum Vanadium Tungsten	Refractory metals for use in fast reactors where their capture cross-sections are acceptable. Choice at present is influenced by many factors which are discussed in the text. Niobium is also a possible metal for use in thermal reactors.
Sodium Sodium-potassium alloy Lithium Bismuth	Liquid metals to be used as heat-transfer media. Choice at the moment is limited to sodium or sodium-potassium alloy. Lithium ^{7} has attractive properties, but the isolation of this isotope is not yet commercially feasible. Bismuth is at present the favored solvent for the fuel in a liquid-metal reactor.
Constructional steels	These range from mild steels to fully austenitic steels and are usually chosen on the basis of their weldability, resistance to particular corrosive conditions, cost, and other factors in specific cases.
Cermets	These will normally be used as fissile or fertile materials or as a mixture of fertile, fissile, and moderating elements. Usually chosen because of some special property not possessed by an equivalent alloy, e.g. a uranium/uranium-carbide cermet is resistant to damage caused by phase-change thermal cycling.

* "Burn-up" is the term used to describe fissioning in the fuel; it is usually expressed as a percentage of the total atoms, e.g. 1% burn-up indicates that 1% of all atoms originally present in the fuel have undergone fission.

† This view might be modified as a result of future research on pyro-metallurgical processing.

‡ Increase in concentration of fissile atoms in the fuel.

Type 1: Light-Water-Moderated and Cooled.

Water is used at high pressure and at temperatures up to 300° C. Severe corrosion problems with water are encountered at this temperature. Alloying of fuel to improve irradiation behavior must also satisfy corrosion requirements in the event of failure of the sheath.

A development of this type is the boiling reactor, in which the water boils in the core. Such reactors have the advantage of avoiding intermediate heat-exchangers, since the steam can be fed direct into a turbine system. Boiling reactors are inherently stable.

Type 2: Gas-Cooled, Graphite-Moderated.

This type forms the basis of Phase I of the power program; gas under pressure is employed to provide adequate ratings. Sheath temperatures possibly range up to 500° C. The problem arises of obtaining sheathing materials of low capture cross-section, high thermal conductivity, and adequate mechanical strength at temperature. Without enrichment not much alloying element can be permitted to improve the irradiation characteristics of the fuel.

Type 3: Sodium-Cooled, Graphite-Moderated.

Higher operating temperatures are possible than with Type I. The problems of high pressure are eliminated, but are replaced by problems of sodium technology. The system has different, and possibly less difficult, corrosion problems than Type 1. Not much alloying element can be permitted to improve irradiation behavior, because the neutron balance is not very favorable.

For subsequent stages of the power program there are other types of thermal reactor which have attractive features, viz.:

Type A: Liquid-Metal Fuel Using the Fuel as Coolant; Graphite-or Beryllia-Moderated.

Probably based on a solution of uranium in bismuth for fuel and coolant. Thorium-bismuth slurry used as blanket for breeding. Problems include mass transfer due to thermal gradients, irradiation behavior of liquids, and stability of slurries.

Type B: Graphite-, Beryllia-, or Beryllium-Moderated with Fissile Material Impregnated in the Moderator, Probably Gas-Cooled.

Problems of the irradiation properties of fissile, fertile, and moderator mixtures arise. Moderator may be graphite, beryllia, or beryllium. In the case of graphite and beryllia the effect of fission fragments on thermal conductivity is likely to be a cardinal point.

Type C: Aqueous Solution of Fissile Material Acting as Fuel and Coolant.

Metallurgical problems are associated with the corrosion of container materials and particularly the influence of irradiation on corrosion.

Other types of thermal reactor have been constructed for special purposes, and these have given rise to particular metallurgical problems which will be referred to later. Two examples are:

Type D: High-Pressure Water Reactor (Light-Water-Moderated and-Cooled) Using Highly-Enriched Fuel.

Small-size system as a result of high enrichment, used in the U.S. submarine project. A major problem is to obtain reliable operation even at the sacrifice of economy. A possibility exists of considerable dilution of fissile uranium by alloying, dispersion in a matrix, or use of ceramic.

Type E: Heavy-Water-Cooled and -Moderated with Highly-Enriched Fissile Material.

Compact research reactors (e.g. DIDO at Harwell and CP 5 in the U.S.A.) operating at low temperature and at high neutron flux. High burn-up of fissile material is required; a possibility exists of dispersing fissile material in a suitable matrix. The choice is widened as compared with Type *D* because of the lower temperature.

Because they represent an advanced stage in the nuclear-power program, designs for fast reactors have not been developed in the same variety as those for thermal reactors, and it is sufficient for the present purpose to consider the general problems of the British fast reactor being built at Dounreay. This is sodium-cooled and charged with fuel elements* consisting of enriched uranium, possibly alloyed to a limited extent (say up to 5 at.-%). Engineering and nuclear factors, and the necessity of limiting the amount of fissile material to be used, have required that the fuel elements should retain a high degree of dimensional stability during their life. Although questions of safety have influenced metallurgical design in this reactor, the most important problem is that of the irradiation behavior of the fuel.

Because of the high gain factor associated with the fast fission of plutonium, fast reactors should eventually be fueled with this element. High burn-up is again of great importance, and the metallurgist has to devise plutonium alloys, ceramics, or cermets with good irradiation stability. Plutonium is a product of both thermal and fast reactors, and it is expected that it will be fed back into thermal systems in spite of its low gain factor in thermal fission. For this application, it will be used either mixed with fertile and/or fissile material, or with non-fissile material in concentrations of about 1%. The metallurgical features of fuels of this type are being investigated.

METALLURGICAL PROBLEMS

From this review of reactor types, it is possible to summarize those metallurgical problems associated with reactors under the following general headings:

* The term "fuel element" is used to describe each unit of fuel in its protective sheath or can.

(1) Irradiation stability of the fuel element.
(2) Thermal stability of the fuel element.
(3) Sheathing materials.
(4) Corrosion
(5) Fabrication.

There are, in addition, fundamental problems which do not arise directly from the reactor program. These are mainly associated with the physical properties of the materials set out in Table I, and include such items as the electronic structures of the elements, diffusion constants, and electrical and thermal conductivities. The long-term influence of the solution of such problems could, of course, be far reaching. Under each of the above headings it is obvious that alloying is of importance, and it is with the development and investigation of alloys for particular service conditions that the metallurgist in nuclear energy is much concerned. The unique service conditions, and the unusual materials which these necessitate, are the chief distinguishing features between this branch of metallurgy and any other. For the most part, methods of investigation are similar to those to be found in any metallurgical laboratory, and there is certainly no difference in the physical concepts employed from those used elsewhere. The dangers consequent on the failure of nuclear plant dictate high standards and very rigorous methods of inspection, but these differ only in degree from those used in other applications.

IRRADIATION STABILITY

Neutron irradiation of fuel and constructional materials in reactors introduces a completely new problem to metallurgical studies. In the fuel the fission process releases large amounts of energy, and not only do the associated fission fragments cause much damage to the lattice, but also the atomic volume of the resulting dispersion of atoms is greater than that before fission occurred. Furthermore, the fission products are chemically different and about 10 at.-% consist of the rare gases krypton and xenon. Three broad effects are, therefore, associated with fission:

(i) Formation of interstitials and vacancies by neutron bombardment and collision by fission fragments.

(ii) Formation of small regions of high temperature, leading to local increases in volume around the fission fragment track ("spike") due to thermal expansion. This introduces internal-stress systems possibly associated with plastic deformation.

(iii) An increase in the number of atoms present, which causes a general tendency towards a decrease in density which may be large if bubbles of the inert gases are nucleated.

Practical experience in reactors in Britain has so far been concerned only with low burn-up, so that the problems arising from (ii) above have been more evident than those associated with (iii). At the high burn-up which will be necessary with economical power reactors, the effects associated with (iii) (i.e. excessive density change and/or fragmentation of fuel) will dominate considerations of fuel stability.

α-Uranium, which is stable up to 665° C., is orthorhombic in structure and has markedly anisotropic properties. Its chief mode of deformation at room temperatures is by twinning. As the temperature increases, more deformation occurs by slip, and above approximately 450°C. slip is the chief mechanism. Cahn[1] has been able to show that in the twinning region the [010] crystal direction is associated with a low yield point in compression, while in tension the yield point is relatively high. Similarly, high compressive yield points and low tensile yield points were found in the crystal directions normal to [010]. Wyatt and Pugh[2] have demonstrated how this anisotropy can play a part in pile behavior. They postulated that the stresses set up in the region of the fission spike lead to anisotropic deformation, causing a change in shape of a crystal which can be related to its crystallographic orientation. Each fission event can be divided into a heating and a cooling period. In the heating period, the material surrounding the fission spike is in compression, and it is postulated that plastic deformation occurs preferentially in the [010] direction of the crystal because of the low compression yield stress in this direction. During subsequent cooling, the compressive stresses are replaced by tensile stresses, and because of the change in yield behavior with the direction of stress, plastic deformation occurs preferentially normal to the [010] direction. The net result of these processes is that a crystal changes shape on irradiation, tending to grow in the [010] direction. In a randomly oriented polycrystalline aggregate, such changes in shape require associated deformations in the bulk of the material if there is to be no internal voidage. At the surface of such a specimen, changes in shape can take place more freely, and crystals having their [010] directions normal (or nearly so) to the surface may be expected to grow outwards and cause irregularities on a previously smooth surface. This phenomenon has resulted in much work directed to ensuring adequate irradiation life in existing reactors and has generally been referred to as "wrinkling." In material which is not randomly oriented but has a marked texture, it is to be expected that the change in crystal shape due to irradiation will cause a change in shape of the whole sample. This has also been observed and has been termed "growth."

Reduction of wrinkling and growth in bulk material can clearly be effected by obtaining a randomly oriented fine-grain crystal structure. It has been shown that this can best be achieved by rapidly cooling through the α-β transformation (β quenching). The efficiency of this treatment has been found to depend markedly on the purity of the material, and it is also sensitive to mass effects, so that results from small laboratory specimens require considerable development to translate them into effective practical processes. Mott and Minty[3] at the Atomic

Energy Research Establishment have investigated the response to rapid cooling of many dilute binary alloys of uranium (containing up to about 3 at.-% of alloying element) and have shown that a fine grain can be achieved in many of them by β-quenching. The kinetics of the α-β transformation are therefore very sensitive to small alloying additions. Transformations in uranium-chromium alloys have been studied in detail in America, but further analysis of systems of this type remains to be undertaken as a general research problem.

The efficiency of small grain-size in reducing wrinkling has been demonstrated, and Leach and Edge[4] have shown that wrinkling reaches a maximum at about 200° C. and falls progressively with a rise in temperature. Work on single crystals at the A.E.R.E. by Plail and Wyatt[5] has confirmed that the growth directions were as predicted and that the process was temperature-dependent, growth being absent when deformation was mainly by slip, i.e., above about 450° C. There does not appear to be a saturation value for growth, and to explain this the theory already described requires that a continuous process of de-twinning should be taking place. While it is feasible to postulate such a process, the high temperatures immediately around the fission spike make investigation difficult.

An objection to the theory is that the lifetime of the fission hot spot is only about 10^{-10}–10^{-12} sec. Very little is known about such high rates of stressing as this would produce, and Frank-Read sources might not operate.

There is an alternative explanation of the observed results suggested by Siegle and Opinsky[6] in the U.S.A., who have postulated that shape change occurs by aniso-tropic diffusion of interstitials or vacancies. On this growth model Seitz has suggested that (100) planes would be removed if vacancies diffused to the dislocation lines of the (010) [100] slip system, while extra (010) planes could be formed by interstitials, giving the observed shape changes. Pugh[2] at the A.E.R.E. has put forward an alternative diffusion mechanism, in which it is suggested that irradiation removes atoms from the close-packed rows parallel to the [100] direction in the (001) planes. The lattice is then maintained: *(a)* by forming extra interstitial close-packed pairs of (100) rows, which causes an extension of the crystals in the [010] direction, and *(b)* by vacant sites in the original close-packed (100) rows diffusing along the (100) rows to the grain boundary, causing a contraction in the (100) direction.

Pugh suggests that the diffusion mechanism can also be used to explain the influence of temperature on irradiation growth. At high temperatures (above 450° C.), the diffusion mechanism becomes inefficient because, with a higher equilibrium concentration of thermal vacancies, there is an increased tendency for vacancies and interstitials to recombine. Below 200° C. (where maximum wrinkling, and hence growth, occurs), the reduced mobility of vacancies leads to an increase in vacancy concentration above the equilibrium numbers present in the absence of irradiation.[1]

It is not yet clear what part these growth phenomena play in the behavior of the specimen at high burn-up when "swelling" occurs. Swelling is the term used in Britain to describe the marked decreases in density observed in some samples irradiated to 1000 MWD/T. Experimental work is not sufficiently advanced to determine whether fine grain in α-uranium significantly reduces swelling. Most attempts to improve the fuel behavior at high burn-up have been made with alloys containing fairly large amounts of alloying element. Predictions of the possible causes of swelling enabled experiments to be designed on five separate lines:

(i) That alloying should produce a material of high creep strength.

(ii) That the structure should be controlled to give a large number of regions of lattice misfit which could provide sinks for the fission-product gases to accumulate harmlessly.

(iii) The elimination of the anisotropic α phase in favor of a stabilized isotropic phase with consequent absence of transformations associated with high strength.

(iv) That the geometric form of the fuel should be such that the fission-product gases could diffuse readily to a free surface.

(v) Restraint of the swelling by mechanical containment of the fuel or other metallurgical device to achieve restraint.

Recent experimental results have helped to define the problem more precisely, and the following summarizes the position. Regions of lattice misfit such as occur between appropriately chosen phases in multiphase alloys do not seem to provide harmless sinks for fission-product gases, and some alloys of this type have shown large changes in density (40% decrease in one case). The swelling generally increases with temperature and at high temperature (e.g. in unalloyed γ-uranium) the observed density decreases agree well with calculations (made independently by Wyatt[7] and by Foreman[8] at the A.E.R.E.) in which the pressure in gas bubbles formed in the material is related to creep strength. Here the creep strength of the material is very low, and the rate of diffusion high enough for bubbles to nucleate and grow, so that a simple mechanical picture of bubble formation in a viscous medium seems to be useful.

However, at lower temperatures (e.g. 500°–600° C.), the observed swelling is much greater than would be expected on the basis of the above calculations, and it is clear that swelling in this range is caused by some other mechanism. Under irradiation conditions there is reason to suppose that internal stresses set up by the anisotropic properties of α-uranium may influence creep behavior. This might mean that the gas-pressure/creep-strength mechan-

ism was still valid, but new creep data appropriate to irradiation conditions would be necessary to settle the point. This calls for investigation of the creep behavior of α-uranium under irradiation, and, although no precise data have been given, Russian work [9] indicates that the creep strength is much reduced. This point is under active investigation in the U.K.

It is to be concluded from this general outline that a strong, isotropic alloy should exhibit good resistance to irradiation damage. Early experiments on uranium-12 wt.-% molybdenum alloys, which were single-phase, isotropic, and strong under the particular irradiation conditions, have shown much less swelling than unalloyed α-uranium or two-phase alloys containing α-uranium. The creep data for these alloys are not yet available for calculations to be made of the swelling to be expected on the gas-pressure/creep strength model. The particular uranium-molybdenum alloy mentioned has ideal metallurgical properties from the point of view of this model, i.e. the isotropic γ phase is easily retained down to low temperatures, and the mechanical strength is good even at very high temperatures (50 D.P.N. and 7 tons/in.^{2} U.T.S. at 800° C.; the value for pure uranium is about 0.05 D.P.N. at 800° C.).

Unfortunately, molybdenum is undesirable on nuclear grounds, especially for thermal reactors. It is therefore of direct practical importance to determine how far the molybdenum content can be reduced without losing resistance to irradiation damage. This problem is likely to be closely connected with changes in microstructural characteristics under irradiation. For example, Russian work [9] has demonstrated that a uranium-molybdenum alloy becomes single-phase on irradiation at a temperature where the equilibrium structure is two-phase, i.e. it changes to a structure normally in equilibrium at a temperture higher than the irradiation temperature. This effect might well mean that, under irradiation, alloys can be retained in the single-phase condition at molybdenum contents lower than those which would appear to be necessary from the equilibrium diagram. Useful compromises between neutron economy and metallurgical characteristics are possible here.

It should be pointed out that only elementary observations on swelling have so far been made. The overall changes in density of irradiated specimens have been measured, and active metallography on sections cut from these have given some indication of the size and distribution of the porosity. However, no studies have yet been made of the mode of nucleation of gas bubbles or its relation to the microstructure. This is a field in which systematic work (with metallurgical condition of the specimen, temperature, and rate and amount of irradiation as variables) must be done to provide the basis of a detailed understanding of swelling. The gas-pressure/creep-strength model gives a broad picture which will probably prove satisfactory for single-phase isotropic materials and possibly also for α-uranium when the correct data are known. However, it is likely to need modification for more complex alloys, where the indications are that swelling is structure-sensitive in a way probably not explained by creep characteristics. Here metallographic study along the lines indicated should lay the basis for defining metallurgical specifications for fuels.

As irradiation swelling seems to be due to the accumulation in bubbles of fission-product inert gases, theoretically it should be possible to eliminate it by arranging for the gas atoms to be removed from the bulk of the specimen by diffusion. Preliminary calculations indicated that there might be sufficient release of gas by direct diffusion if the greatest distance to a free surface from any point in the bulk of the specimen was less than about 10 μ. It was realized that this condition could be achieved by powder metallurgy, using a loose-sintering technique. By the appropriate choice of temperature, powder particles of 20-μ dia. could be sintered to about 90% of the theoretical density while still retaining a high degree of interconnected porosity. Unfortunately, the swelling observed on loose-sintered powder compacts is not significantly different from that on solid cast material, and the amount of gas released is very small. It may be that the diffusion rates are lower than expected, but an alternative explanation is that there are enough nucleating points even in the small particles for most of the gas atoms to form bubbles before reaching a free surface. The results so far obtained have been at temperatures in the region of 600° C., and there is a possibility that at higher temperature (e.g. in γ-uranium) the rates of diffusion are high enough for a large fraction of the gas to escape, but this is less likely if the alternative explanation just described is valid. This problem is still being investigated, but, because the fuel temperature in most reactors at present considered is below 600° C. at some point in the core, loose-sintered powder compacts of small particle size are unlikely to provide a solution to the irradiation problem.

In the United States a direct approach has been made to the problem by mechanically inhibiting the swelling by enclosing the fuel in a strong can. If the can completely surrounds the fuel, a decrease in density is opposed by hydrostatic pressure. If the fuel is not fully enclosed, a density decrease can be accommodated by extrusion of the fuel in the unrestricted direction, leaving the can effectively unchanged in shape. Both these methods are feasible, and the problems involved are largely the practical ones of arriving at a compromise between adequate strength in the can and an acceptable loss of neutrons by parasitic capture. However, from the fundamental point of view, determinations of the magnitude of the necessary restraining forces would help in defining the mechanisms of swelling.

In addition to methods of external restraint, three other possible ways of restraining the fuel exist. The first is the so-called "dispersed"-type fuel element, in which the fissile particles are distributed discretely throughout a non-fissile matrix. The number and size of the particles should be such that each is completely surrounded by the matrix, which then behaves as a restraining medium. The experimental results so far available on this type of fuel are very promising, and, from a metallurgical point of view, there appears to be no reason why complete burn-up of the fissile atoms should not be achieved. There are several practical disadvantages, however, mainly connected with the dilution of the fissile material; this leads to parasitic loss of neutrons in the matrix and therefore restricts the choice of carrier metals to those of acceptably low capture cross-section. In addition, practical restrictions on reactor size require a high concentration of fissile atoms, which means the use of either plutonium or enriched uranium; with the present availability of fissile material, such fuel elements are likely to be restricted to use in research reactors or for units where the cost of power is not the first consideration, e.g. for submarine propulsion or for power production in isolated areas.

The second method of restraint exploits the characteristic property of certain microstructures of exerting what has been termed "internal restraint." An example of this is provided by a uranium/uranium-carbide cermet which has been prepared by Williams[10] at the A.E.R.E. by a direct reaction between uranium metal and graphite powders under the appropriate conditions. With the correct carbon content (2 wt.-%) and heat-treatment, the microstructure consists of a network of uranium carbide (UC) surrounding islands of metallic uranium. Cermets with this structure can be made with a density of 15.5 g./c.c. ,and they have been shown to withstand thermal cycling across the α-β phase change without suffering the distortions associated with uranium. It is believed that the dimensional stability during thermal cycling is due to the restraining action of the carbide network on the metallic uranium, and on this basis swelling should also be inhibited during irradiation. The advantages of this type of fuel lie in its high uranium density and the absence of parasitic neutron loss in thermal reactors.

A further possibility of achieving restraint with good neutron economy is by a non-uniform distribution of alloying element through the cross-section of an element. Alloys likely to withstand irradiation damage because of their high strength (e.g. uranium-12 wt.-% molybdenum alloy) contain more alloying element than is desirable for neutron economy in power reactors, and this militates against the use of homogenous alloys of this type for fuel. It is, however, feasible to consider surrounding low-alloyed uranium with a skin of highly-alloyed uranium of high strength, so that the core is restrained while the average amount of alloying element is acceptable. Proposals of this kind are being investigated; in addition to the question of irradiation behavior, there are problems of fabricating duplex material with components of different properties. Powder metallurgy offers an elegant method of making this type of element, but the reactivity of the powders may present difficulties in large-scale production.

It should be noted here that the large temperature gradients that exist in a fuel element under power introduce complex stress systems. In experimental work with small-scale specimens,* it is difficult to stimulate these gradients, and one of the present problems is to interpret results from these investigations in terms of a full-scale element with large temperature gradients, which may be as high as 1,000 C./cm. This difficulty is now being resolved by the provision of high-flux research reactors and the development of "loop"† experiments. The high flux enables lower enrichments and larger cross-sections to be used, and one of the purposes of the "loop" is to provide adequate cooling so that power-operating conditions can be simulated.

At the present stage of the atomic-energy program, radiation stability is one of the most important problems and an increase in the life of a fuel element is a very significant factor in reducing the cost of nuclear power. There is no doubt that long irradiation life can be achieved; the main problem is to do this with acceptable neutron economy. Following the lead from basic research results, the task of future fuel development will be to find economic compromises between irradiation damage, parasitic neutron loss, and other properties such as corrosion.

There are already firm indications that ceramics will behave better under irradiation than metals, but development of their use is likely to depend upon the availability of fissile material because of their lower effective fissile density. In the second and third stages of the power program, this objection will be much less important, and the application of ceramic fuels will be much more extensive. Nevertheless, ceramics have their own special irradiation problems, the most important being brittleness which leads to break-up under the thermal stresses in a reactor. Although break-up probably does not significantly influence the dimensional stability of an element, it means that the fuel cannot be used as a load-bearing unit, and engineering design must depend on the canning material or other device for structural strength. Design work still remains to be done to determine fully the effect of this on neutron economy.

The effect of irradiation on the mechanical properties of fissile material is important if the fuel is used structurally, and this problem is also being investigated. In addition, irradiation effects on physical

* So far, small specimens have been necessary because the neutron fluxes available require highly enriched fissile material to give the desired burn-up in a reasonably short time. The opacity of uranium to thermal neutrons increases with the enrichment, and to achieve acceptably uniform irradiation throughout the bulk of a specimen the size must be kept small. For this reason nearly all work on high burn-up at the A.E.R.E. has been done on specimens of about 4 mm. dia.

† In nuclear-energy work the term "loop" is used specifically to mean an experimental facility in which there is a forced flow of coolant. An "in-pile" loop is an irradiation facility of this type.

properties such as thermal conductivity will change the temperature gradients in the fuel, and this, combined with possible loss of ductility, may lead to failure by thermal stressing.

So far mention has been made only of solid materials, but it is evident that several of the difficulties described could be overcome by the use of a liquid fuel. For example, fission-product gases should be readily removed, so that the problem of swelling should be absent and nuclear poisoning reduced. In addition, the charge and discharge of a liquid fuel from the core of a reactor would be relatively simple, and this would afford the possibility of continuous (or frequent batch) chemical processing, thus eliminating nuclear-poisoning problems and, because of the absence of irradiation damage, allowing complete burn-up of the fuel. The adoption of liquid fuels at an early stage of the power program has been prevented by the absence of a liquid uranium alloy of sufficiently low melting point and containing enough fissile material. It now seems unlikely that a liquid alloy will be found which contains sufficient uranium to enable it to be used without high enrichment. The possibility of finding a useful liquid alloy of plutonium still remains. Attention has, therefore, been concentrated on dilute solutions of uranium in low-melting-point metals, it being recognized that pure fissile material would be required for a practical-sized reactor. The problems of liquid and liquid-type alloys are discussed below.

THERMAL STABILITY OF THE FUEL ELEMENT

Instability of fuel elements due to the thermal conditions within a reactor can arise from four main causes:

(1) Chemical or diffusion interaction between fuel and can.

(2) Mechanical interaction between the can and fuel on repeated thermal cycling.

(3) Repeated thermal cycling of the fuel.

(4) Thermal stressing caused by temperature gradients.

The best-known example of reaction between fuel and can has been provided by early experience with aluminum canning, where it was found that UAl_4 could be formed by direct attack. The cans ruptured because of the local deformation due to the volume change associated with the formation of the relatively low-density compound. With simple canning techniques, where the temperature and the thermal rating of the fuel are low, barrier layers of inert material have been effective in preventing reaction. A further solution, at present being employed in the British prototype power reactors, has been to use magnesium cans, as there is no reaction between uranium and magnesium. For more highly-rated fuel elements, such solutions are undesirable because of the temperature drop at the interface, which might increase the temperature of parts of the fuel beyond the α—β transformation, thus creating a further cause of instability. To reduce the interfacial temperature drop (which can be as much as 100° C.), good thermal contact can be achieved by "bonding," but it is necessary for the bond to be stable and for diffusion or reaction between the materials to be slow (bonding is also necessary for other reasons to be discussed below). So far bonding has been considered seriously for: *(a)* low-temperature reactors with aluminum sheaths, and *(b)* zirconium cans for high-pressure water reactors with surface temperatures of about 300° C. The formation of low-melting-point eutectics (~700° C.) with iron and nickel has led to some doubts about the use of bonded mild steel or stainless steel because of the probable difficulties of controlling the bond in production. The field here remains relatively unexplored, and it would seem that there is scope for more research on solid-state reactions between uranium and various canning materials.

For reactors using liquid-metal coolants (e.g. the sodium/graphite thermal reactor and the British fast reactor), the problem of heat transfer between fuel and can is most easily solved by including liquid metal in the can. It should be noted that there is no reaction here between coolant and fuel, so that the can forms a structural unit rather than a protective sheath.

Most of the possible canning materials have coefficients of thermal expansion sufficiently different from that of uranium to give rise to "thermal ratcheting" unless special precautions are taken. For example, the coefficient for magnesium (26×10^{-6}/°C.) is much higher than the average value for uranium (18×10^{-6}/°C.) so that on heating a magnesium-canned bar of uranium the can becomes longer than the fuel rod. In a gas-cooled reactor operating at pressure, the magnesium would collapse on to the fuel, and on cooling there would be some plastic deformation in the can due to the tensile stress set up because of its greater coefficient of expansion. Continued cycles of heating and cooling would lead to further plastic strains, which would eventually cause failure of the can. Two methods of preventing this type of racheting failure are feasible: *(a)* the uranium could be loose in a very strong can which would not collapse and would therefore allow contractions of fuel and can to take place independently, and *(b)* the fuel and can could be so closely held together that they would behave as a single unit.

The first method is generally not practicable because of the thickness of can required. The conditions needed for the second method are best met by metallurgically bonding the fuel to the can, but where this is impossible, mechanical devices for reducing relative movement between the fuel and can could be tried. However, for high-pressure water reactors, where canning with zirconium (coefficient of expansion 6×10^{-6}/°C.) is attractive, mechanical bonding is much less desirable because of the need for high thermal ratings and because of the special corrosion problems. Bonding has been investigated

by high-temperature duplex rolling and extrusion, by powder-metallurgy techniques, and by casting the fuel into zirconium cans, which behave as molds. Each of these techniques gives bonds which have distinct metallographic and corrosion properties. Although bonding processes of this type are under active investigation both here and in the U.S.A., it is evident that much more work will be necessary before the properties of the bond are fully understood.

The other main phenomena affecting thermal stability derive from the anisotropic thermal expansions in α-uranium and from the density changes between α- and β-uranium and between β- and γ-uranium. The mean coefficients of thermal expansion of α-uranium between 25° and 625° C., given by Foote,[11] are 35.16×10^{-6}/°C., -8.49×10^{-6}/°C., and 32.62×10^{-6}/°C. in the a, b, and c directions, respectively. The anisotropy of the plastic properties and its temperature-dependence have already been referred to and this, combined with the expansion anisotropy, causes plastic strain when the metal is cycled over a range of 500° C. Rolled α-uranium has a mixture of two component textures—one with (010) planes normal to the axis and the other with (110) planes normal to the axis—the proportions varying with the temperature of working. On thermal cycling, a ratchet mechanism (due to a change in plastic properties with temperature) operating between the two component textures causes a progressive increase in length and decrease in diameter of a bar. Pugh[13] has shown that there is a rate-controlling process operating at the high-temperature part of the cycle which has an activation energy equal to that for self-diffusion in uranium. He suggests that this process is probably creep within the grains. It appears to be very efficient and can produce elongations of about 8%/100 cycles. In coarse-grained material, a similar mechanism causes wrinkling.

Few reactors have yet operated at fuel temperatures where phase changes occur, so that there is no operational experience of phase-change distortion. Experimental work on unalloyed uranium has shown that cycling through the α—β phase change can lead to serious alterations of shape and density. It has been shown that phase-change damage can be inhibited by mechanical restraint. "Internal restraint" produced by the network structure in a uranium/uranium-carbide cermet also prevents this kind of damage.

SHEATHING MATERIALS

In the early reactors, aluminum was used for sheathing because it was a commercially available metal of low neutron-capture cross-section, which could be readily fabricated and welded. In alloyed form it is still a possible material for use with high-pressure water reactors operating at surface temperatures up to 300° C. The trend is, however, to higher temperatures, and a wider range of sheathing materials is necessary. In fast reactors, more metals are permissible because of the lower capture of high-energy neutrons, and even for thermal reactors the scope will be widened by the use of plutonium or enriched uranium.

The special properties required in a canning material, such, for example, as high-temperature strength and compatibility with coolant and fuel, lead to the selection of unconventional metals which have hitherto been exploited only on a small scale and for limited uses. There is thus a new field for metallurgical research on the range of metals indicated in Table I. At this stage the problems are general, since the knowledge of most of the pure materials is scanty, and often no work at all has been done on alloying. New methods of extraction are sometimes desirable because the existing small-scale methods are not suitable for large-scale development.

Niobium provides a typical example of a metal in this category. One of the chief problems in preparing a good metallurgical product of acceptable ductility is the control of oxygen content, and a large amount of work on extraction processes for niobium has had to be done to produce an understanding of the variables which affect such control. Successful application of niobium depends upon its being able to withstand attack by molten uranium (or an alloy of uranium) under certain conditions which might arise in the reactor. The metal must also retain its properties in the environment of the coolant (sodium in this instance) during the life of the fuel element. On theoretical grounds two effects might occur: *(a)* the oxygen might be removed by uranium in contact with the niobium surface, and *(b)* niobium might take up oxygen by the reduction of sodium oxide.

In the future there will be more emphasis on the mechanical strength of the sheathing and constructional materials and, for the reasons already discussed, this trend will be emphasized if ceramic fuels are used.

There remains therefore the general problem of alloying to give improved mechanical properties, and, because of high-temperature applications, creep strength and ductility are likely to be the most important properties. It should be noted here that an essential additional property is good weldability, unless "integral" methods of fabrication can be used.

Recent work on zirconium provides an example of research directed to producing high-strength alloys. Two general types of alloy system appeared to justify creep investigations. The first of these, represented by zirconium-tin and zirconium-aluminum, shows a marked increase in solid solubility with temperature, leading to a peritectoid transformation. In the second, represented by zirconium-molybdenum, there is a eutectoid transformation. The problem has been to relate creep behavior to the heat-treatment and microstructure of these alloys. The results so far indicate that the solid-solution alloys have better creep properties than the eutectoid alloys, but it is already clear that there is unlikely to be a simple interpreta-

tion of the data in terms of the observed microstructural changes.

The ideal sheathing material from a nuclear point of view is beryllium, but metallurgically it presents some unique difficulties. As an engineering material, its ductility is very low at room temperature, and the causes of this have been the source of theoretical speculation and much practical investigation. The axial ratio of this hexagonal metal is abnormally small, and Pugh has suggested that the brittleness is connected with this and is therefore an inherent property of the material. His view has not, however, been fully accepted, and it has been suggested that if the material could be obtained in a sufficiently pure form, it would be ductile. Much ingenuity has been exercised in developing practical methods of purifying beryllium, but it is too early yet to reach a conclusion on the causes of its brittleness. Fabrication methods for sheet have been evolved, which give ductility in the plane of the sheet, but not in the perpendicular direction. Alloying has not been successful in improving ductility of beryllium because of the ready formation of compounds. These stable compounds are brittle, and when formed in cast material they do not refine the grain-size (which is always large) or improve the properties. Attempts to produce a network of ductile metal (e.g. aluminum) around particles of beryllium by powder-metallurgy methods have also failed to improve mechanical properties. In most cases of mixed elemental powders, the XBe_{13} compounds are formed at the sintering temperature, porosity develops and, sometimes fragmentation of the compact occurs. The absence of ductility at room temperature in beryllium may not be a serious obstacle to its use in reactors, since the brittle → ductile transition occurs at about 200° C., and in most reactors in which it would be used the temperature exceeds this figure. Although this has not yet been proved in practice, there is good reason to hope that beryllium, brittle at room temperature, will be satisfactory as a canning material, particularly as the metal is by no means fragile at low temperatures. The major problems associated with beryllium will probably lie in its production on a large scale and its economical fabrication.

Some problems have arisen with conventional materials because of attempts to modify them for particular applications. For example, the use of magnesium in a power reactor gives cause for concern because of the risk of fire. Work pioneered by Huddle [14] at the A.E.R.E. shows that alloys can be made oxidation-resistant even above the melting point by the addition of small amounts of beryllium (up to 0.1 wt.-%) and calcium (up to 0.2 wt.-%), the beryllium being added as aluminum-5 wt.-% beryllium hardener. It was soon found that the addition of the optimum amounts of these elements for improving the corrosion-resistance led to difficulties with weld cracking, so that work had to be undertaken to define compromise compositions, and this has produced the series of "Magnox" alloys.

CORROSION

Corrosion in nuclear-energy work includes corrosion in aqueous, gaseous, liquid-metal, and fused-salt media. For metallurgical development, much attention has been given to aqueous and liquid-metal phenomena, in the former case with emphasis on behavior in high-pressure water. In the next few years, this work will be extended to boiling reactors,* where both steam and water are simultaneously present and the gas/liquid interface moves irregularly. More complex phenomena than have been encountered so far in high-pressure water can be expected, particularly as there are likely to be local and short-lived temperature fluctuations associated with steam-bubble formation.

Zirconium provides an example of the wide influence of corrosion research on manufacturing policy. For pressure-water reactors, neutron-economy considerations have led to the choice of this metal for canning, although mild or austenitic stainless steel would satisfy the corrosion conditions. Autoclave testing of zirconium alloys, particularly in the U.S.A., has led to a working specification for a corrosion-resistant alloy (Zircaloy), in which upper limits are set to the nitrogen (100 p.p.m. by weight) and carbon (400 p.p.m. by weight) contents. This specification has required modification of the manufacturing process to maintain these limits; for example, melting of zirconium in graphite crucibles is not permissible because of carbon pick-up. This has stimulated research in consumable-arc methods of melting and alloying, and particularly on their application on a large scale. There is still much scope for fundamental research on the properties of this type of arc and their relation to variations of composition in the alloy. Because of practical demands, development work tends to be too far ahead of basic research in this field.

Zircaloy, mentioned above, is a complex alloy, containing, in addition to 1.5 wt.-% tin, small amounts of iron 0.07-0.20 wt.-%, nickel 0.03-0.08 wt.-%, and chromium 0.05-0.15 wt.-% (although recent work has suggested that, of the iron, nickel, and chromium, nickel alone, in the correct amount, is sufficient). It has been shown that the tin preferentially forms a compound with nitrogen, which then no longer impairs the corrosion-resistance. However, a full explanation of the function of the iron, nickel, and chromium is still awaited. This problem has an analogue in the Magnox alloys, to which higher oxidation-resistance is imparted by trace quantities of beryllium and calcium. The theoretical aspects of these effects have been discussed recently by Huddle,[15] but more fundamental work needs to be done on the properties of metallic surfaces, and any associated layers of chemical compound, to confirm his ideas.

This point is emphasized by the discovery with zir-

* Boiling reactors are inherently stable systems, and they have the advantage of avoiding intermediate heat-exchangers, since the steam can be fed direct into a turbine system.

conium alloys of "breakaway" corrosion, in which rates of attack suddenly increase after a period of relative inertness varying from a few hours to hundreds of days. The presence or absence of corrosion products is also known to influence corrosion behavior, and autoclave test results (in which corrosion products are not removed) must be interpreted cautiously in predicting pile behavior, where there is a rapid flow of coolant and removal of such products. For this reason, in-pile "loop" experiments are necessary, and in the next few years this type of test, requiring extensive engineering effort will increase.

For the reasons given above, zirconium sheathing is preferably bonded to the fuel, which should also be corrosion-resistant. Experiment has shown that in high-pressure water at 300° C. uranium-molybdenum alloys are initially corrosion-resistant if they are in the γ phase region, but that precipitation of α promotes corrosion. It therefore appears that alloys with 12 wt.-% molybdenum must be used, as the γ phase cannot be retained below this content at the operating temperature. However, further investigation has revealed two problems. The first of these is connected with the bond which, in some circumstances, has been shown to be subject to rapid attack when exposed in a defected zirconium can. The width of the bond can be varied according to the method and temperature of fabrication, and information from the U.S. suggests that there is more susceptibility to attack when the bond is wide. It also appears that the attack is more rapid if access of cooling water to the corrosion site is restricted, suggesting that some type of regeneration of the active corroding agent is involved. The second phenomenon is the sudden rapid corrosion of the fissile alloy after periods of immunity varying again from a few hours to hundreds of days. It has been suggested that this may be related to the formation of hydride by hydrogen diffusion. These examples illustrate the complexity of the corrosion problems in nuclear-energy work, and they show that there must be caution in extrapolating results obtained from tests which are not completely representative of pile behavior, especially when the basic mechanisms of the process are not understood.

Aluminum-nickel alloys are being investigated as a cheaper material to replace zirconium in pressure-water reactors.

A further problem on which little work has yet been done is that of the effect of irradiation on sheath and fuel corrosion. From this point of view, four effects are likely to be important: (1) change of phase in complex alloys, (2) the effect of build-up of fission products and the possible consequent change in structure, (3) change in chemical nature of the corrosion medium due to irradiation decomposition, and (4) change in surface properties due to damage by fission fragments. This last point is of considerable importance if the corrosive medium is a fissile solution, since fission fragments are formed at the metal surface.

In the liquid-metal field, the corrosion mechanisms are not, of course, of electrochemical origin. Reaction between solid and liquid metals can occur in five ways: (i) by solution of the solid by the liquid, (ii) by solid solution of the liquid in the surface layers of the solid, (iii) by intercrystalline penetration by the liquid metal, (iv) by formation of intermetallic compounds between liquid and solid, and (v) by impurities in the liquid promoting chemical-compound formation between liquid and solid metal.

In (i) and (v) solid metal is removed or taken into solution, and because of the temperature-dependence of both these processes, "mass transfer" occurs. In all reactors, temperature differences in the fuel and in the coolant circuits are inevitable, and if there is any liquid solubility of the constructional materials they will dissolve to the greatest extent at the high-temperature part of the circuit and be precipitated in the cooler part if the solubility limit is exceeded. The coolant is thus left unsaturated when it returns to the hot part of the system and the process is repeated.

The mechanism of (v) above is different, and is best illustrated by reference to sodium and ferrous constructional materials. It has been shown that "mass transfer" is accelerated in sodium circuits when the oxygen content of the sodium exceeds about 30 p.p.m. by weight. With very pure sodium, mass transfer is practically eliminated. Horsley [21] suggests that, at high temperatures (above 300° C.), the oxygen enables a mixed oxide [$(Na_2O)_2.FeO$] to be formed and that this is unstable at lower temperatures, releasing the oxygen for further attack. The answer here is obvious and has led to work on the preparation and handling of pure sodium, which now has its own technology.

Attempts to prevent the seizing of sliding parts by solid-phase welding in sodium circuits are being made by surface coating the parts with adherent and non-reactive ceramics.

Mass transfer due to solubility changes can be avoided by exploiting (iv) above and deliberately promoting stable-compound formation. The Brookhaven Laboratory of the U.S. Atomic Energy Commission [16] has provided an answer in the case of a dilute solution of uranium in bismuth. It has been found that addition of zirconium to the liquid metal inhibits mass transfer by the formation of zirconium nitride on the surface of the steel structural components. There is usually sufficient nitrogen present in the steels for the nitride to be formed.

Intercrystalline penetration is clearly of great importance for stressed parts, and the possibilities of stress-corrosion cracking and corrosion-fatigue must not be overlooked. The influence of pile irradiation is again of great importance, particularly where an inhibition mechanism depending on surface phenomena is involved.

FABRICATION

Although most of the metallurgical effort in nuclear-energy research is devoted to fabrication, many of the problems are more in the nature of development than of basic research. The techniques for both research work and industrial-scale production are dominated by the high reactivity of the metals being used. Not only are they easily oxidized, but many of them also readily attack container and die materials. These features are accentuated by the need for many of the processes to be carried out at high temperature, and hence high vacua are used extensively.

There are several fields where new processes and methods of approach would be useful. At present there is much interest in "integral" canning, in which the fuel and sheath are completely bonded together, thus eliminating fusion welding. This can be partly achieved by duplex extrusion, but end caps and a fusion weld or braze are still required. Some experiments at the Massachusetts Institute of Technology have shown that full integral canning is possible by extrusion of a specially built-up billet. This is composed of alternate layers of fuel and sheath material, all fitted into a container of the sheath material. After extrusion, the rod consists of sheathed fuel separated at appropriate intervals by sheath material over the whole cross-section. The extruded bar can be parted at these points. This type of complex extrusion could also be applied to the fabrication of fuel having a non-uniform distribution of alloying element. In such processes, attention should be given to the properties of the interfaces between the various components. The importance of this has been pointed out in connection with the zirconium/uranium-molybdenum couple, the properties of which are much influenced by extrusion temperature. Integral canning can also be achieved by rolling, but as yet this has been successful only with flat plates. The solid-phase welding properties of the materials are vital to the success of the rolling method, and there is scope here for more basic research, since it would be advantageous to reduce the amount of deformation required.

Powder-metallurgy methods offer a flexible and elegant means of fabrication. The extreme reactivity of the materials, and the large surface areas of the powders, require the techniques to be meticulously controlled. Press capacity limits the size of fuel element which can be readily made by conventional powder techniques, and this has led to work on hydrostatic pressing. As yet, this has been done only at room temperature, so that the materials must be subsequently sintered. To take advantage of the properties of hot compaction and to be able to fabricate to the required size, the hydrostatic method is being developed for use at high temperatures. Successful development on these lines should increase the scope of powder metallurgy.

Direct extrusion of powders at high temperatures has given good-quality solid metal. An extension of this method to form cermets by chemical reaction of the components *in situ* has been found to give metallurgical structures which could not otherwise be obtained, e.g. the uranium/uranium-carbide cermet. This technique could be applied to other duplex systems, particularly where density differences might lead to segregation when using fusion methods.

Two other, closely allied, fields of fabrication study are consumable-arc melting and welding. The consumable-arc melting process offers possibilties of refinement which have not been fully explored. Welding problems must usually be treated specifically, but an essential feature of nearly all joining of metals in the atomic-energy field is the need to relate the properties of the welded joint to the corrosion conditions in service.

The fabrication processes discussed above are complex, and the problems arise from this complexity. It is of interest to note that, beyond the immediate future, the trend for some reactors may be in the opposite direction and less precise fabrication may be acceptable. This changed concept arises from the possibilities of cheap processing by pyro-metallurgical methods which do not fully decontaminate* irradiated fuels. The partial-decontamination costs should be low, and less emphasis need be placed on irradiation stability because frequent processing becomes possible. This, however, requires active handling which might become uneconomical unless it is simple. This is a development which is likely to be of interest in fast reactors of the Dounreay type, and, for example, the sodium-cooled, graphite-moderated thermal reactor. Both of these are sodium-cooled, and as there is no serious problem of fuel corrosion, perfect sealing of the can is unnecessary. With sodium as a heat-transfer layer, the size tolerances for the fuel are greatly relaxed, and relatively crude methods of fabrication are acceptable.

The cost of forming and sheathing fuel elements represents a major item in the economics of the nuclear power program and considerations such as those discussed in the last paragraph might well determine the trends in reactor design.

Mention has been made of the feed-back of plutonium into thermal systems, though the toxicity of this α-active material will present serious problems of handling on the scale that will be required. Again, the economics of the active fabrication process might be a decisive factor in this type of fuel cycle.

ALLOYING AND PHYSICAL PROPERTIES

Among the metals considered in this paper are several whose natures are notably different from those which are being extensively studied elsewhere with a view to obtaining some understanding of the metallic state. There are the so-called "refractory" metals, such as zirconium, niobium, and molybdenum, and the fuel metals, thorium, uranium, and plutonium, as well as others connected with the more specific problems.

*Removal of activity associated with fission products.

In these two groups, the complex electronic structures lead one to expect divergences from the simple principles upon which much of the behavior of metals such as sodium, copper, and even the transition metals of the iron group can be explained. The electronic structures are so far removed from the models on which any mathematical calculations are based that experiment is necessary to establish validity or limitations of any of the current theories of metals. The A.E.R.E. have therefore fostered studies of physical properties and general alloying behavior of the metals, but only a few typical examples can be given here.

Pfeil [17] has examined the solid solutions of zirconium, niobium, and molybdenum in γ-uranium, since these elements have favorable atomic sizes for solid-solution formation and probably have effective valencies of 4, 5, and 6, respectively. The systems have shown extensive solid solubility—with niobium and zirconium, complete miscibility at high temperatures dividing into two solid solutions at lower temperatures. Current theories suggest that the miscibility gap in the niobium system may be a function of the electron: atom ratio, but this could not hold for the zirconium system as well. Hence, suitably chosen ternary systems based on these two binaries are being investigated to discriminate between this and other possible explanations.

Simultaneously, the magnetic susceptibilities of these alloys are being systematically examined, and it is hoped to determine eventually such properties as the low-temperature electronic specific heats. From such a combination of evidence, it should be possible to deduce the effective valency of the solvent metal.

The elements of the Seventh Period are especially difficult to understand, since the information derived from a wide variety of experiments shows that there is a very delicate balance between the alternative electronic arrangements energetically possible for elements in the neighborhood of uranium and plutonium, so that a given metal may show different valences according to circumstances (such as its atomic environment in an alloy, chemical compound, or even allotropic form).

The physical behavior of plutonium, which has six modifications, is complex, one of the most interesting features being the negative temperature coefficient of expansion in the face-centered, cubic δ phase.[18] One suggestion to explain this, postulated by the Plutonium Section of the A.E.R.E.,[19] is that in δ-plutonium two possible electronic configurations can exist and that, with an increase in temperature, the one having the smaller atomic diameter is formed at the expense of the other. This is only one of several possible explanations; in each there are objections either on theoretical grounds or because of a contradiction between some of the experimental facts. The subject is too extensive for further discussion here, but it is typical of the problems which work on the heavy elements is producing.

Another important field of research is that concerned with diffusion. Data are being found for the various metallic systems relevant to reactor applications, so that quantitative estimates can be made of the effects suspected to depend on diffusion processes. One example is the determination of the diffusion of argon in silver, intended as an analogy to the diffusion of inert-gas fission products in fissile materials. LeClaire and Rowe [20] showed, by an elegant activation technique, that argon entrapped in silver foil diffused out at a rate comparable with normal metallic diffusion, but that, once it left the metal lattice at a free surface, there was no mechanism whereby it could re-enter and diffuse through the lattice. From this it is inferred that gaseous fission products diffuse until they reach or form a free surface, resulting in internal bubble formation and causing the "swelling" previously described.

For studying metals by diffraction techniques, the use of neutrons offers two distinct advantages over X-rays. First, there are large variations in neutron scattering between neighboring transition elements, so that the atomic positions of each in an alloy with another can be readily distinguished; for example, superlattices in iron-cobalt and nickel-manganese alloys are easily detected. Secondly, atoms having a magnetic moment cause additional neutron scattering, and hence the magnitude and direction of these moments can be determined. This property gives a direct method of investigating anti-ferromagnetism. Studies of magnetic neutron scattering probably offer the greatest promise of advance on fundamental problems of magnetism and, in contrast to the mean moments given by normal measurements, neutron diffraction can ascribe magnetic moments to individual components in ferromagnetic materials.

A novel field of alloy study is being developed for "slurry" fuels and blankets.* Slurries can be made either by cooling an alloy from the liquid to a temperature between the liquidus and solidus of the system or by mixing insoluble particles in a liquid metal. Slurries are of interest because, at practicable temperatures, higher densities of fissile material can be obtained with liquid-type properties than with true solutions. Useful systems of the second type are found in lead-uranium, bismuth-uranium, and bismuth-thorium alloys. In the lead-uranium system, for example, the slurry consists of particles of UPb_3 in a liquid solution of uranium in lead. Interesting problems of behavior arise from the change in solubility of the uranium with temperature. As the temperature of such a slurry system is cycled, the change in solubility gives rise to changes in particle size, shape, and distribution. In a constant temperature gradient, the solid particles may migrate to the low-temperature part of the system. Studies of these effects and assessment of their influence on pile operation are being intensified to provide data for liquid-metal reactors.

* Fertile material surrounding the core of a reactor: neutrons produce fissile material by capture.

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The first nuclear reactor built for private industrial research was placed in operation in June 1956. It is a 50,000 watt research reactor, designed and built by Atomics International, a division of North American Aviation, Inc., for the Armour Research Foundation. Located on the campus of the Illinois Institute of Technology, the reactor is intended solely for peacetime use by industry; it will not be used to generate electrical power.

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A STUDY OF BARGE HULL FORMS

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HISTORY

The development of barge hull forms parallels the commercial exploitation of the inland rivers of the United States. The first rafts of logs poled down the Mississippi gave way to wooden barges lashed to steamboats as early as 1832. By the late seventies, fleets of barges became common. With the development of the iron and steel industries the movement of coal became of increasing importance. The flat boats, which had been too cheap to warrant return upstream, were replaced by more permanent types of barges. In the decade 1910 to 1920, steel was introduced as a hull material, but the construction methods employed evolved barges which could carry little, due to excessive internal structure.

In the Rivers and Harbors Act of 1910, Congress authorized the Secretary of War to design and construct two experimental towboats together with a suitable complement of barges for towing and delivering supplies along the Mississippi and its tributaries. The Board appointed by the Chief of Engineers made a thorough study of all available design and operating information, and conducted a series of model and full scale trials of towboats and barges. The resulting published data constituted the first step in the improvement of barge hull forms for river transportation.

River traffic was drastically reduced in 1914 and 1915; in 1918 much of the river tonnage was destroyed or carried away by ice floes which filled the rivers. The situation was greatly improved in the twenties when the government sponsored programs for the canalization of the Ohio and also established the Federal Barge Line. These advances were followed by projects for the improvement of the Upper Mississippi, the Missouri, the Tennessee, and the Illinois Rivers.

About this time, forerunners of the modern common carrier barge line appeared. The improvements resulting from the studies of 1910 to 1915 began to be put into use. The Corps of Engineers Towboat Board was reorganized in 1928, and a complete analysis was made of the latest practice in water transportation on the Mississippi and its tributaries.

During the period between 1930 and 1940, barge operators and builders began to utilize model basins for the improvement of individual barges and flotillas. With the increase in industrial activity in the Gulf States, the movement up river of large cargoes steadily increased and savings in barge resistance became increasingly important.

As inland river barges improved, so did the barges employed in the harbors of the United States. These barges, used for short hauls by alongside or astern towing, evoked novel problems in resistance and directional stability. Barges came into existence which were especially designed for the movement of any number and variety of cargoes. Weatherproof covered barges, tank barges, merchandise carriers, automobile carriers, car floats, and many other types were used in both commercial and military operations.

The entire inland and intra-coastal waterway system, with dependable river stages and efficient towboats and barges is now an extremely important factor in the nation's transportation system.

TRANSPORTATION CORPS BARGES

At the end of World War II, the Army Transportation Corps was employing a heterogeneous collection of river, harbor, and seagoing barges which had been procured prior to and during the war. In the stress of wartime, little attention had been paid to the design of hull forms or even to the simplifying of structural design details.

To evaluate these barges in light of later day requirements and modern design techniques, a series of model tests was set up for both resistance and directional stability measurements of the existing designs. Each barge model was towed at three different drafts, and trim was varied during directional stability tests. This program included tests on a total of twelve barges. Seven of these were existing types; five were post-war designs. In this article the results of tests on ten of these barges are presented. The bow and stern profiles and body lines of these barges are shown in Figures 1 through 11. Dimensions given are those of the model.

MODEL TESTING BASINS

The eleven barge model tests reported in this article were carried out in two model testing tanks. Barges C, E, I, and J were tested in the Naval Tank at the University of Michigan. Barges A, B, D, F, G, and H were tested in Tank No. 1 at the Experimental Towing Tank, Stevens Institute of Technology.

The Naval Tank is 360′ long by 22′ wide by 10′ deep. Models are towed under a carriage which spans the basin and runs the full length of the basin along rails mounted atop the basin walls. The carriage is propelled at constant speed by means of a traction motor mounted on the carriage.

Stevens Tank No. 1 is 100′ long by 9′ wide by 4.5′ deep. Models are towed from a dynamometer riding on an overhead control rail. The dynamometer is propelled by means of a continuous wire running along the rail and around a motor driven pulley. A direct current motor is used to accelerate the model up to towing speed and an alternating current sychronous motor mounted on the same shaft is cut in to tow the model at constant speed down the tank.

In the prediction of full scale resistance values, the model results from both tanks are equally reliable. In the prediction of full scale yaw characteristics, however, the larger size tank and the type of carriage propulsion employed in the Naval Tank permit the quantitative prediction of yaw; the directional stability results from the Stevens Tank are qualitative only. In the Naval Tank the model can swing freely in full yaw amplitude throughout several cycles. The smaller dimensions of Stevens Tank No. 1 do not permit full swing of a badly yawing barge, and it is seldom that a model can complete more than one and one-half cycles. Also, the cutting in of the synchronous motor often gives an abrupt acceleration to the model. If the model is not headed straight down the tank at this instant, the first swing is overemphasized. Thus, although the complete correction of model yaw in this tank can be considered indicative of full scale performance, uncorrected yaw amplitude cannot be predicted with any degree of accuracy.

EXPANSION OF MODEL TEST RESULTS

The expansion of all model results covered in this article has been in conformance with standards set forth by the Society of Naval Architects and Marine Engineers in Bulletin 1-2 of the Hydromechanics Sub-Committee. The Schoenherr Friction Formulation was used for both model and full scale. A constant addition of 0.0004 was made to the frictional resistance coefficient for roughness. All full scale predictions are based on immersion in salt water at 15° Centigrade.

For the purpose of comparing the results of the resistance tests of all eleven barges, the model results have been expanded to a full scale waterline length of 100 feet, regardless of the length of the original barge. Based on this length the dimensions and principal hull form coefficients are given in Table 1. Curves of total resistance are given in Figure 12.

FACTORS AFFECTING BARGE RESISTANCE

The original barge model testing program was so planned that modifications could be accomplished on each barge form to improve resistance and yaw characteristics. The program thus permitted a limited study of those factors which influence performance.

TABLE I

Barge Dimensions, Ratios, and Coefficients Based on 100 foot Length

	A	B-1	B-2	C	D	E	F	G	H	I	J
Length in Feet	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100 00	100.00	100.00
Beam in Feet	19.91	28.41	32.56	23.24	33.33	21.88	25.66	18.82	27.05	27.38	27.74
Draft in Feet	4.48	6.89	2.96	6.97	4.69	5.47	5.18	4.57	6.56	6.39	7.12
Displacement in tons, S.W.	212.70	488.6	236.8	421.3	430.0	283.2	325.5	219.3	428.1	417.9	469.4
Length-to-Beam Ratio	5.022	3.250	3.071	4.303	3.000	4.570	3.898	5.314	3.697	3.653	3.606
Beam-to-Draft Ratio	4.448	4.150	11.000	3.333	7.109	4.000	4.953	4.119	4.125	4.286	3.889
Displacement Length Ratio	212.7	488.6	236.8	421.3	430.0	283.2	325.5	219.3	428.1	417.9	469.4
Block Coefficient	0.835	0.872	0.859	0.909	0.961	0.826	0.857	0.890	0.844	0.835	0.831
Prismatic Coefficient	0.847	0.900	0.922	0.911	0.961	0.850	0.914	0.896	0.846	0.851	0.848
Maximum Section Coefficient	0.986	0.969	0.932	0.998	1.000	0.972	0.937	0.996	0.998	0.981	0.980
Waterplane Coefficient	0.921	0.988	0.991	0.991	1.000	0.925	1.000	0.976	0.950	0.982	0.981
Vertical Prismatic Coefficient	0.907	0.883	0.866	0.917	0.961	0.893	0.857	0.914	0.889	0.850	0.847

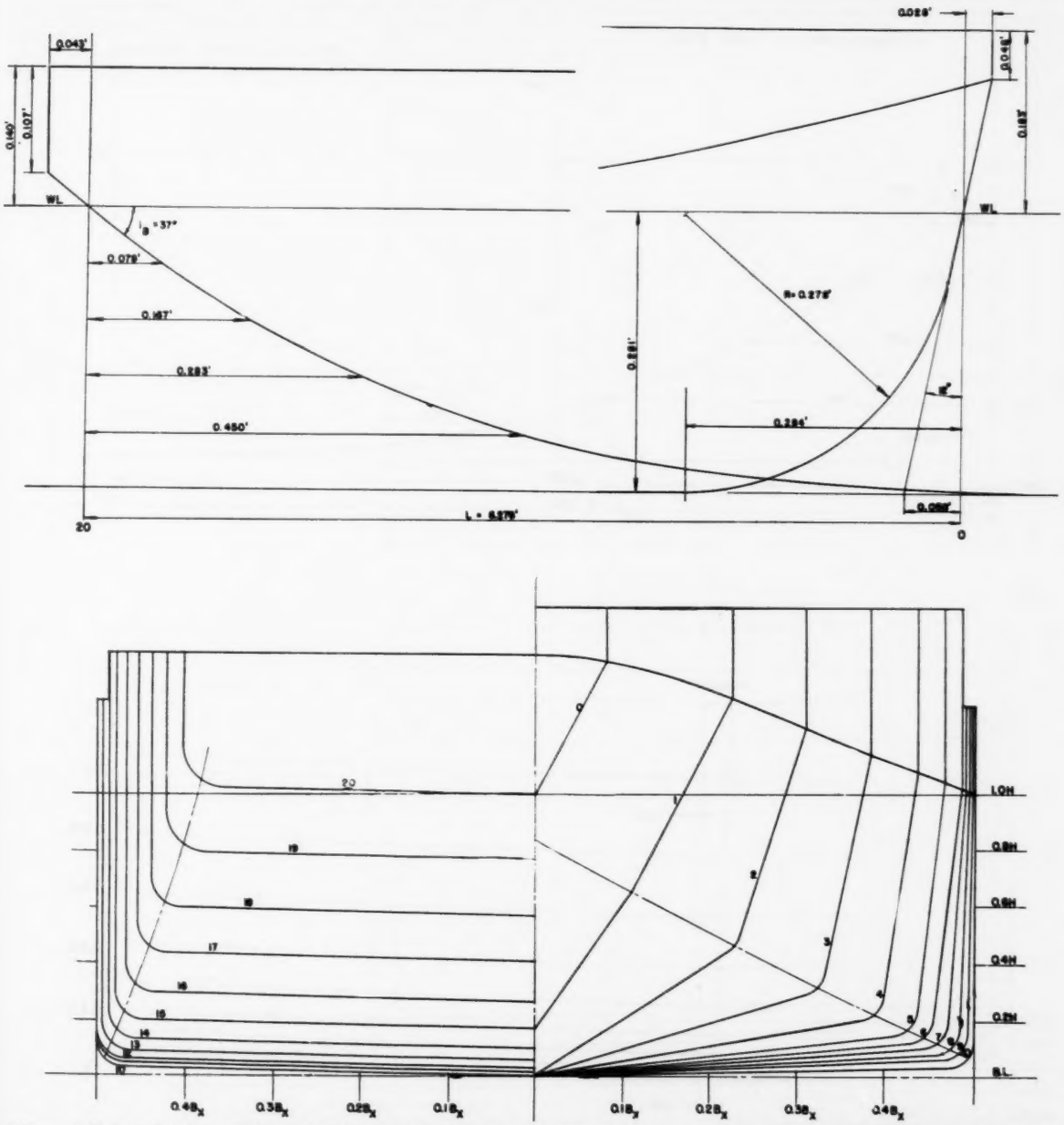

Figure 1. Bow and stern profiles and body lines of Barge A. This 210′x40′x9′ seagoing barge was in active service during World War II. It is representative of seagoing barges employed in commercial service, but with more complicated forebody lines. Ingall's patented pyramid type skegs were used to correct yaw.

The experimentation undertaken on Barge B included construction of three sets of additional bow and stern rake ends. These rake ends had parabolic profiles. The sectional area curves of all three sets were identical. The profile areas, however, were varied, with the sectional area retained by varying the fullness of individual sections. The profile area coefficients, i.e., the ratio of profile area to the circumscribing rectangle, were designed with values of 0.67, 0.75, and 0.83 for the three sets of rake ends.

Regardless of what combination of rake ends was used, the resistance results at all speeds were identical. These tests led to the preliminary conclusion that the shape and slope of the rake profiles are important from a resistance standpoint only insofar as they affect the sectional area curve.

This conclusion was further supported by the results of tests on bow modifications made on Barge D. In this model it was found that little improvement resulted from a careful fairing of the forward rake end when the original sectional area curve was retained.

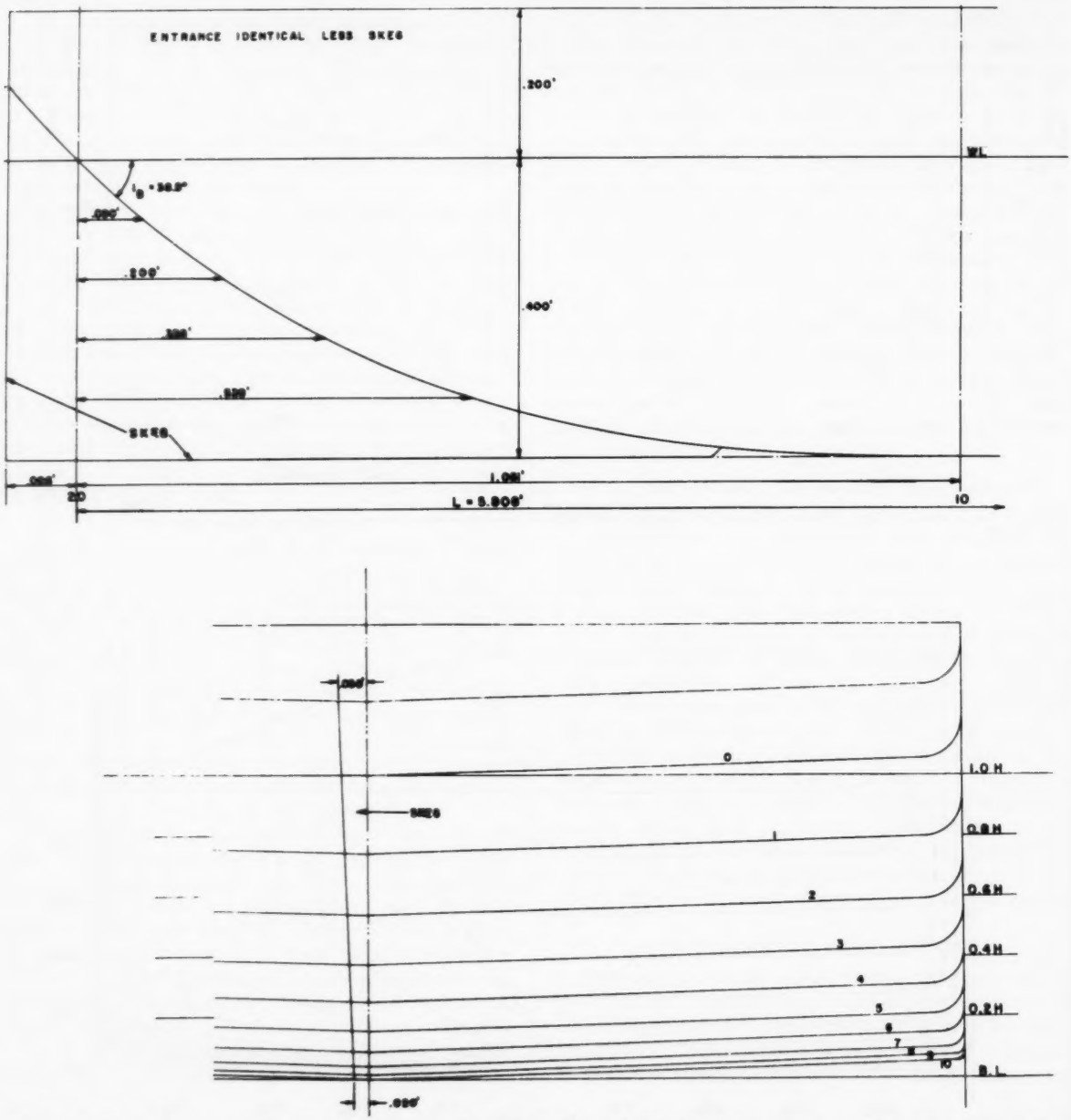

Figure 2. Bow and stern profiles and body lines of Barge B-1. This 120'x33'x8' harbor barge was produced in large numbers during World War II and resembles barges commercially employed in similar service. A single centerline skeg is provided for directional stability.

Several years ago at the University of Michigan, Professor H. C. Sadler carried out a series of experiments to determine the optimum rake end slope for barges. He concluded that a slope of 30° at the waterline was the most desirable. When his results are reanalyzed and the sectional area curves of his models are studied, it appears that the model with the 30° rake angle has the fairest sectional area curve.

Another factor which was studied in the Transportation Corps tests was rake end length. Barge D, which initially had the shortest rake ends of the models tested, was altered to provide a progressively longer bow rake end. Test results indicated a decrease in resistance as the rake end was lengthened, as would be expected. There appears to be an optimum rake end length when resistance is compared with displacement tonnage. A series of tests at the University of Michigan established the optimum length of the forward rake end to be 25% of the length overall. It was also found that the after rake end could be of the same form as the forward rake, but with the after end cut off to reduce the after

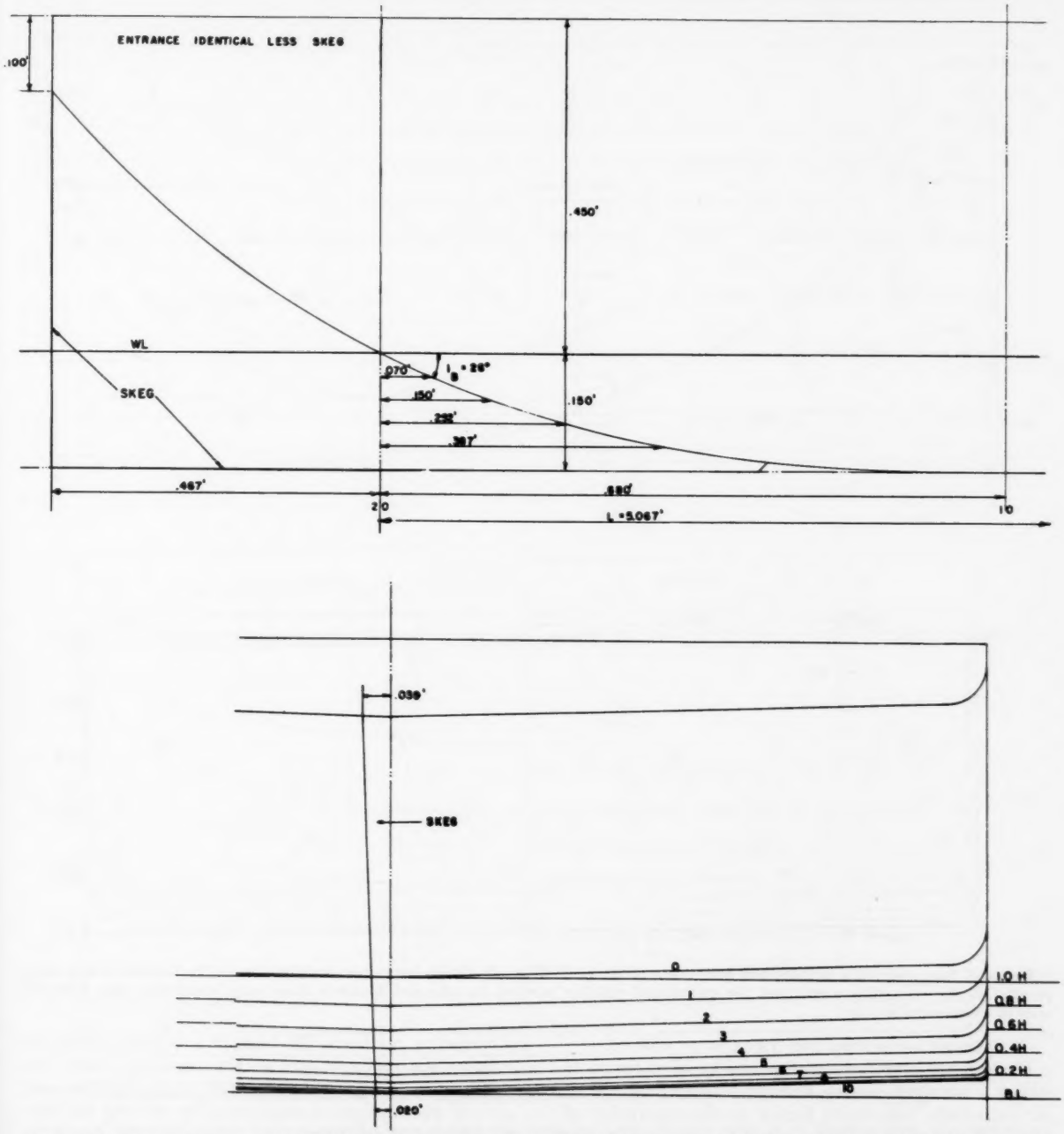

Figure 3. Bow and stern profiles and body lines of Barge B-2. These lines represent the same barge depicted in Figure 2. They have been redrawn on the basis of the 3'-0" waterline used for shallow draft tests.

rake length to 85% of the forward rake length.

Testing a series of barge models at three different drafts offered an opportunity to evaluate the gross effect of draft on resistance. For each barge model the ratio of the resistance at shallow draft to the resistance at maximum draft was plotted against speed. The resulting curves indicated little variation with speed for each draft. Therefore, for each draft, an average resistance ratio was obtained. The plot of resistance ratio versus draft ratio for all barges tested is given in Figure 13.

It can be seen from this plot that, from 50% to 100% load draft, the resistance is directly proportional to the draft. Below 50% draft the resistance ratio rises above the line of direct proportionality. These results indicate that for similar types of barges the resistance will vary as the linear dimensions of the cross section.

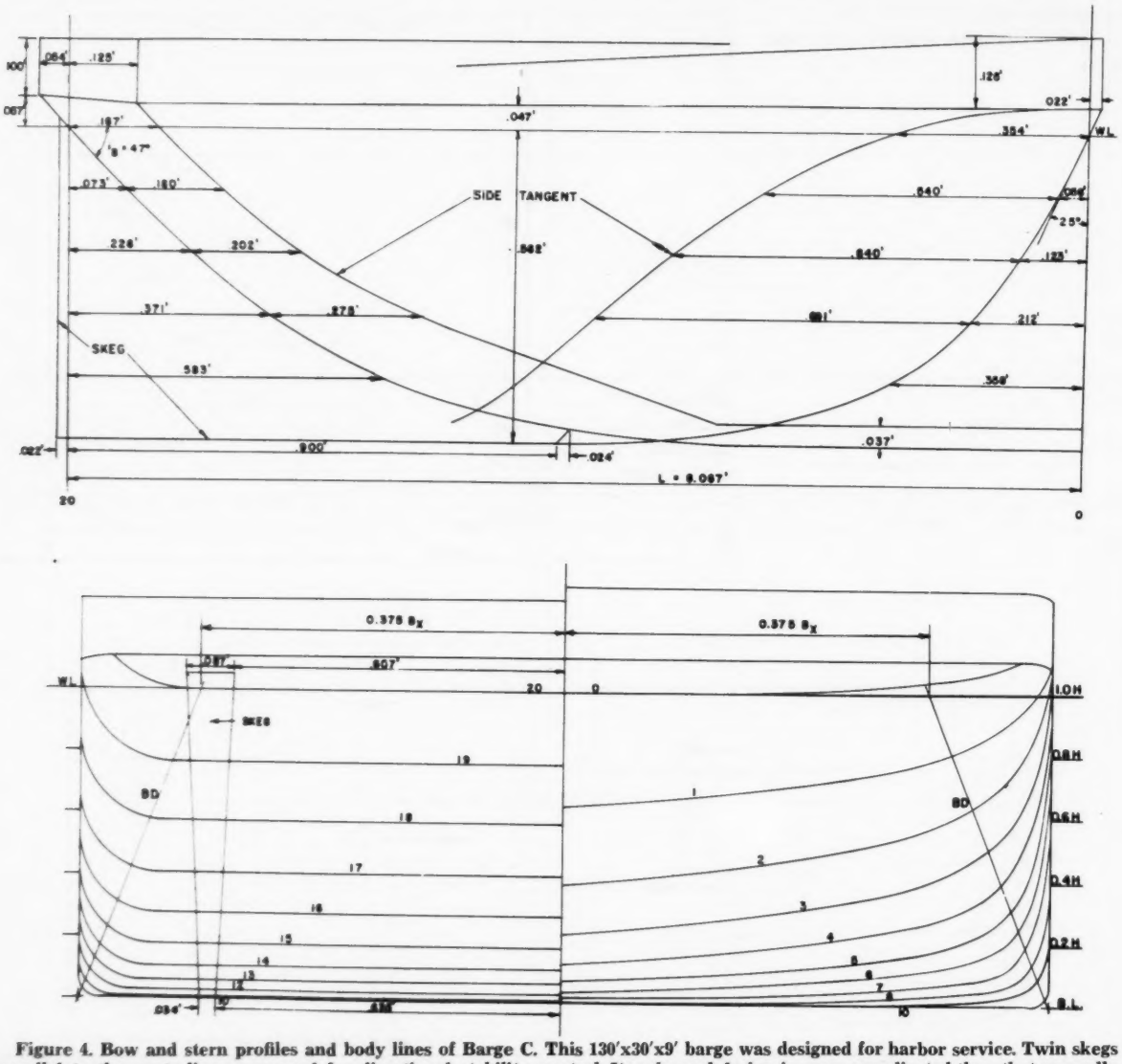

Figure 4. Bow and stern profiles and body lines of Barge C. This 130'x30'x9' barge was designed for harbor service. Twin skegs parallel to the centerline were used for directional stability control. Its rake end design is more complicated than that normally seen in commercial service.

FACTORS AFFECTING THE YAWING OF BARGES

Directional stability, or the ability of a barge to follow a straight course behind a towing vessel, is an extremely important factor in the operation of tugs and barges. A yawing barge is a danger to navigation and to the towing vessel. The veering of a barge in a turn has been known to overturn the towing vessel. Yawing also greatly reduces the efficiency of the towing operation.

When an external force, such as a wave, throws a barge off course, a new transverse resistance force is added. If the moment of this force about the center of gravity opposes and exceeds the restoring moment of the force exerted by the towline, the barge will be directionally unstable.

Directional stability may be restored by several alternative methods. The use of a towing bridle increases the moment arm of the restoring force; the use of plate skegs or a rudder decreases the moment arm of the transverse resistance by moving the center of lateral resistance aft; trimming the barge by the stern moves the center of lateral resistance aft and also, by relocation of the center of gravity, increases the moment arm of the restoring force; fining the forward profile or filling out the after profile tends to move the center of lateral resistance aft; adding a drag at the stern gives an additional restoring moment.

Studies at the University of Michigan concluded that a bridle length of 1.5 barge beams was the most effective in overcoming yaw. Bridles of this length are now in almost universal use for astern towing

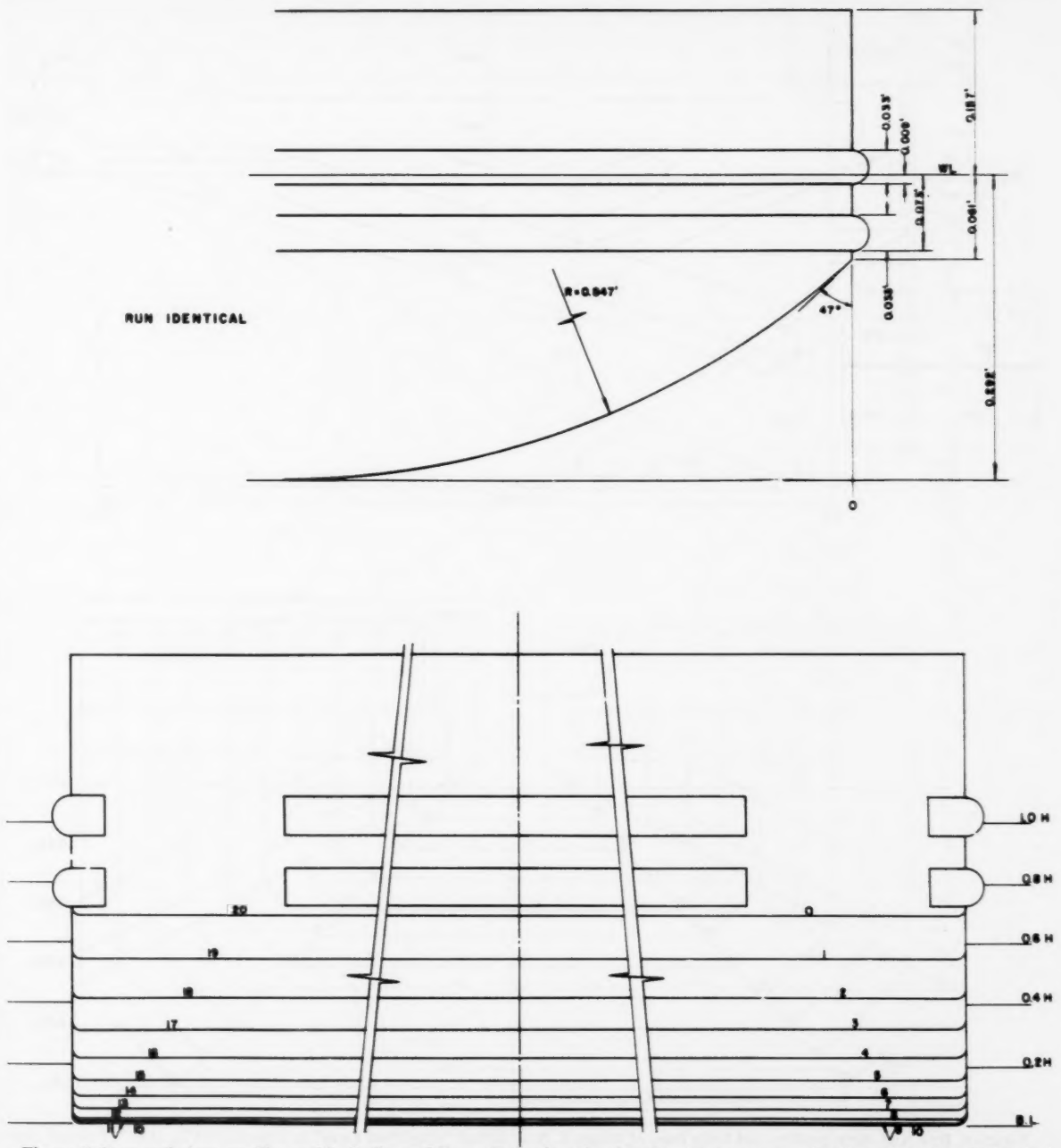

Figure 5. Bow and stern profiles and body lines of Barge D. Designed primarily to serve as a floating pier, this 150'x50'x7' barge is of interest from a towing standpoint because of the necessity of towing it overseas for forward area service. No skegs were incorporated in the original design.

and thus additional yaw correction devices need not be designed to provide greater directional stability than that required for towing with a bridle.

Originally Barges B and C were provided with plate-like skegs to reduce yaw. The model tests indicated that the skegs made no difference in either yaw or resistance. Both barges were directionally unstable as designed.

Barge E had an after rudder which proved entirely ineffective in the model tests when held in a fixed position. Rudders, both bow and stern, have proven notoriously useless on barges since the helmsman can seldom anticipate yaw. Once yaw has started the tremendous transverse forces involved are usually beyond the capabilities of a helmsman to cope with.

Trimming a barge by the stern can be effective in overcoming yaw. The yaw of Barge D could not be

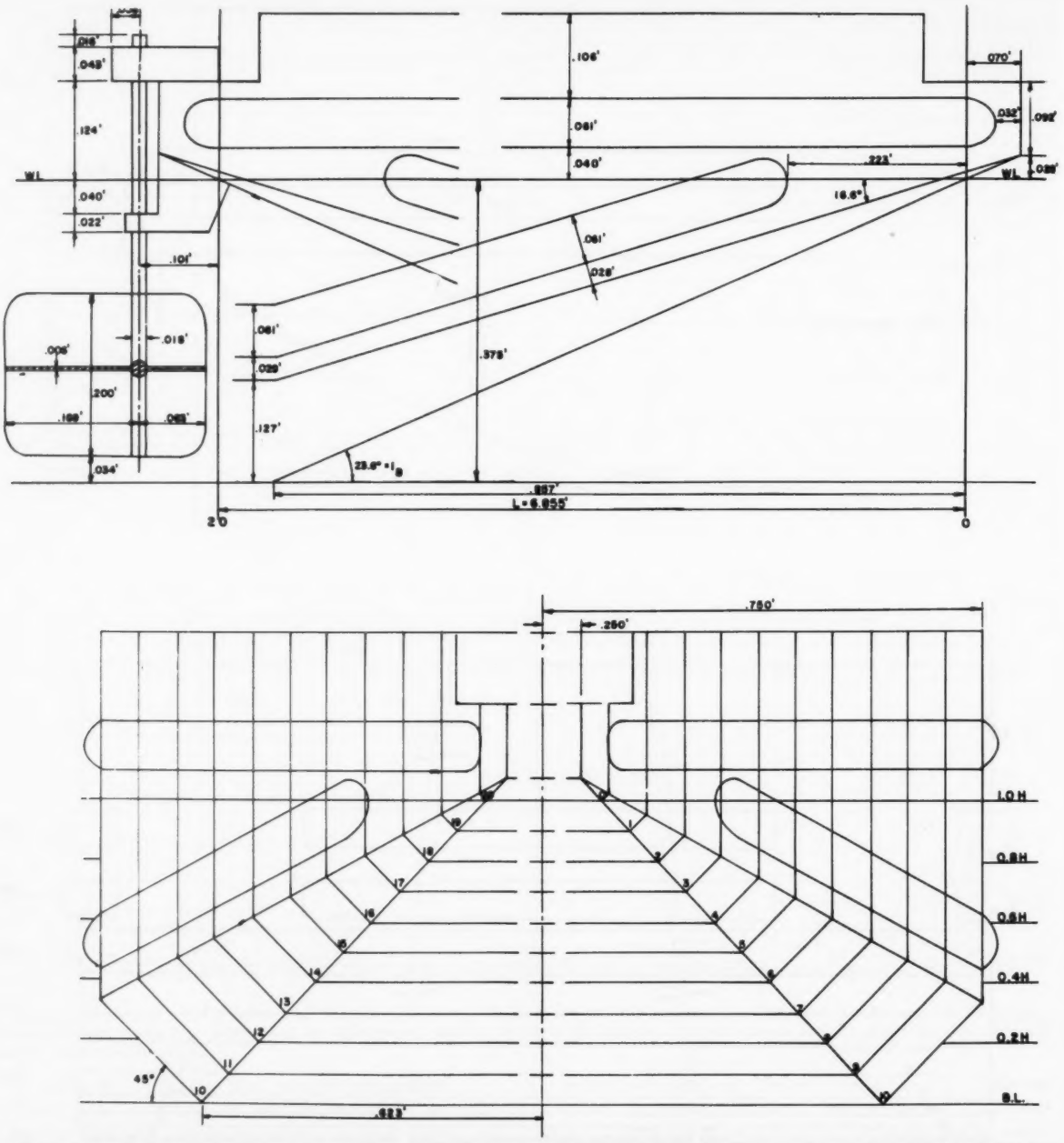

Figure 6. Bow and stern profiles and body lines of Barge E. A so-called "simplified form" is represented by this 112'x24'x6' harbor barge. It was a result of World War II expediency. A manned rudder was installed to control yaw under tow.

controlled by any other method in spite of the fact that three skegs with heavy drags were added. However, when the barge was trimmed one foot by the stern, the yaw ceased. This is generally an undesirable condition from the standpoint of loading cargo and for shallow draft operation.

Tests on barges B and D were performed to attempt to reduce yaw by altering the lateral resistance of the rake ends. The specially designed rake ends for Barge B which were mentioned earlier were combined in such a way as to move the center of lateral resistance as far aft as possible. The effect on yaw was negligible. A similar experiment was conducted on Barge D where the forward rake end was lengthened and carefully designed for minimum transverse resistance. Again yaw was not affected. It was concluded, therefore, that little improvement in directional stability could be obtained by this approach.

The most effective method of overcoming yaw of

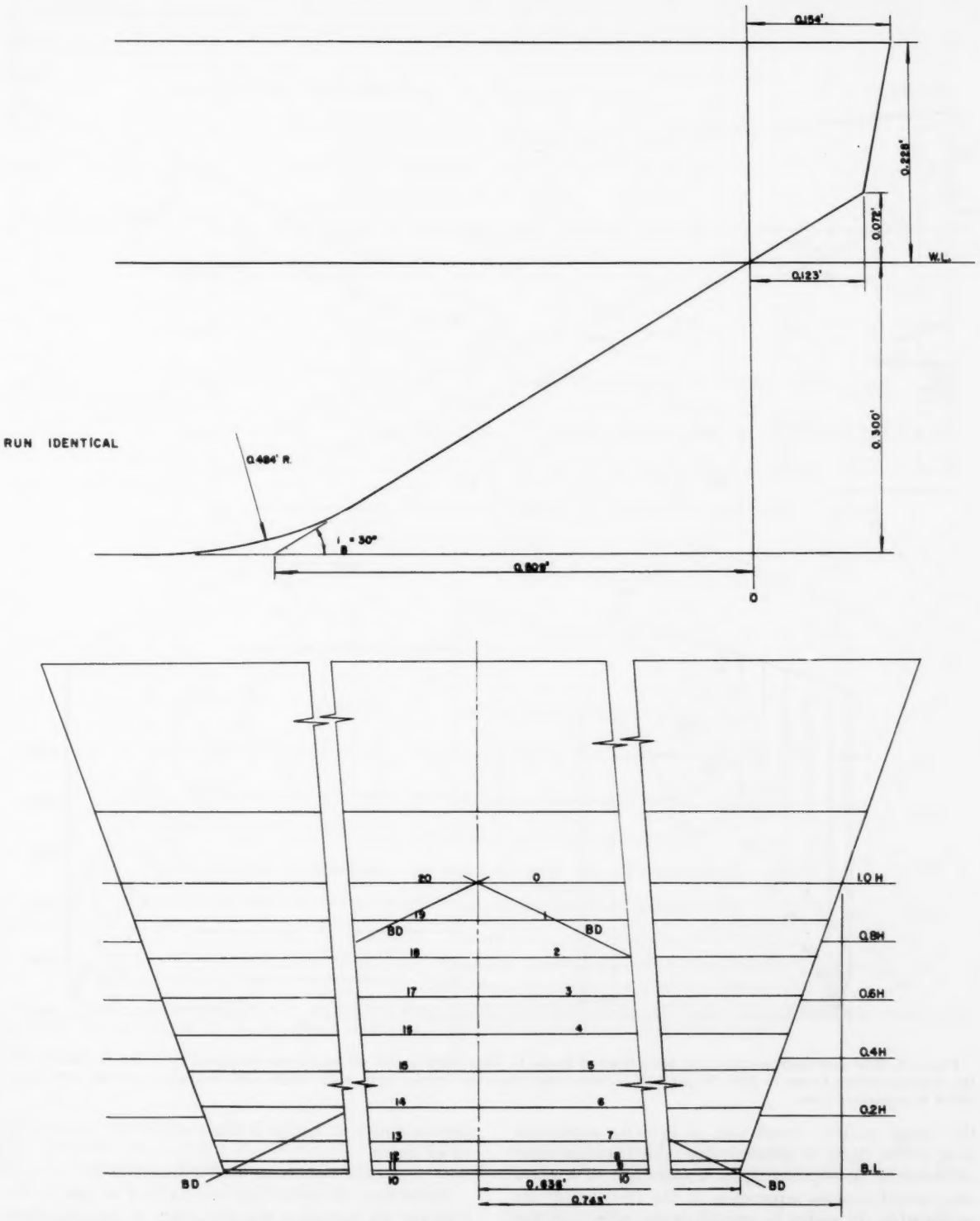

Figure 7. Bow and stern profiles and body lines of Barge F. The 81′x20′x4′ barge depicted here is a special purpose design of 1947 vintage. It was sectionalized to permit breaking down into small sections which could be nested within each other and carried by rail. No provision was made for control of yaw.

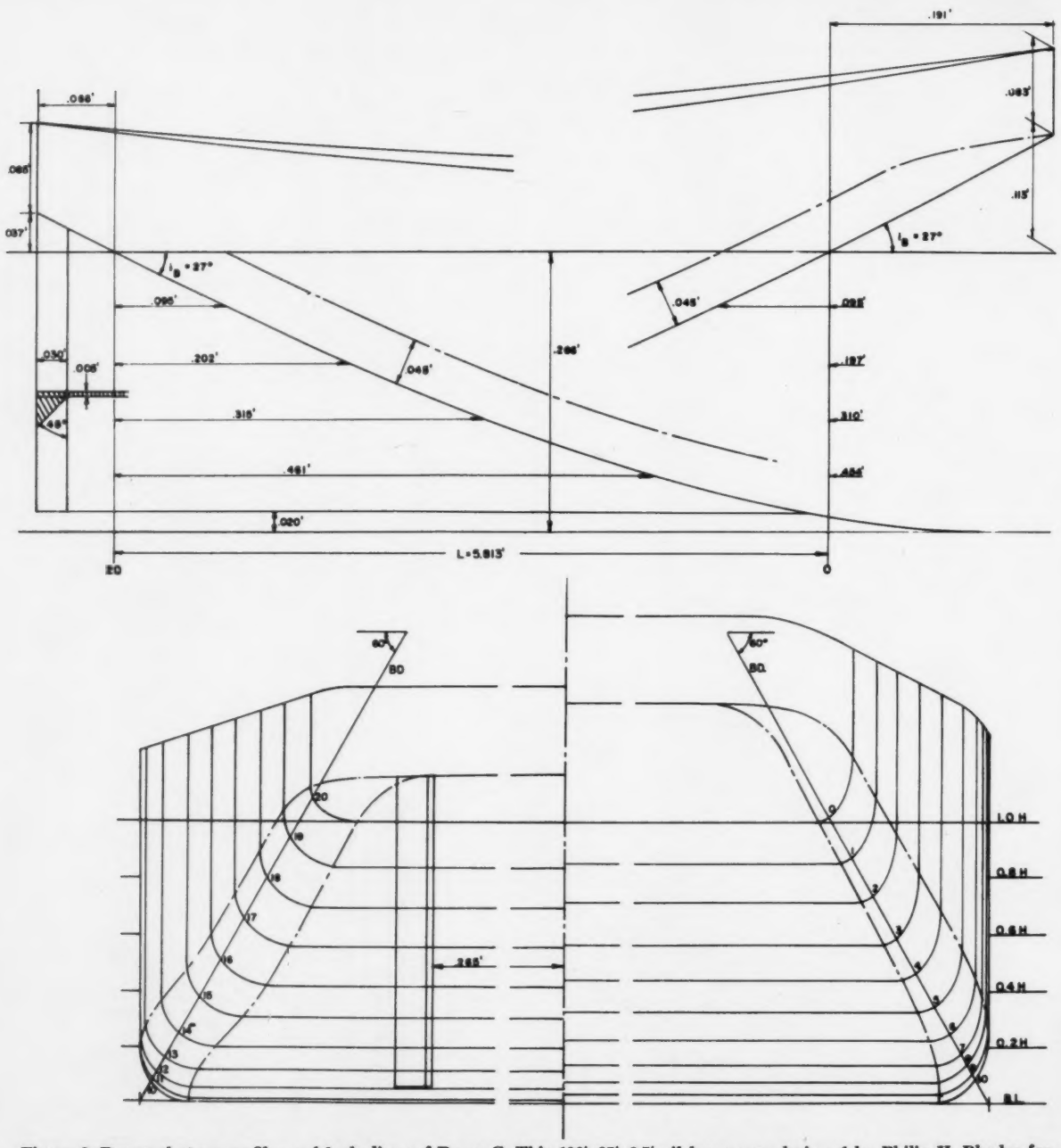

Figure 8. Bow and stern profiles and body lines of Barge G. This 196'x35'x8.5' oil barge was designed by Philip H. Rhodes for the Transportation Corps in 1949. As a result of other tests reported herein, twin plate skegs with triangular prisms were provided to overcome yaw.

the barge models tested was to provide additional drag at the stern. In general, this added resistance is attained by incorporating an appendage to a plate skeg which causes separation of the flow as far aft as possible. In order to minimize the effect on the resistance of the barge, the amount of skeg drag should be no more than that necessary to overcome yaw when the barge is towed with a bridle. With the exception of Barge D this method was successful in all cases.

COMPARISON OF BARGE RESISTANCE

Expansion of model test results to a length of 100 feet for all barges is the first step in placing them on a comparable basis. The primary purpose of barges is to carry cargo and the cargo carrying capacity is a function of the displacement. It is, there-

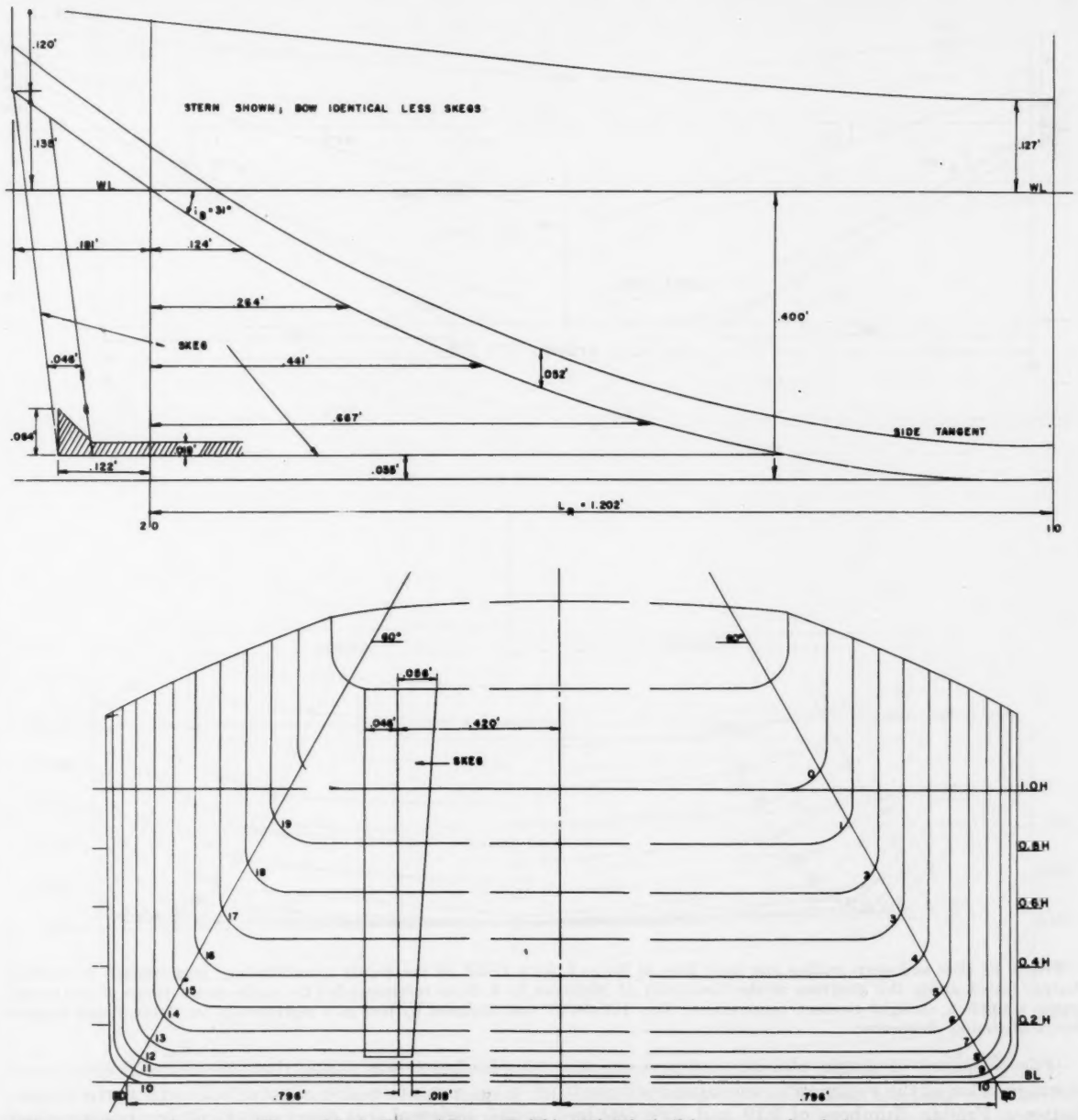

Figure 9. Bow and stern profiles and body lines of Barge H. This 130'x33'x8' oil barge was also designed for the Transportation Corps in 1949, by John H. Wells, Inc. Skegs similar to those on Barge G were provided on this vessel.

fore, desirable to compare the resistance of barges in relation to their displacement.

The factor chosen for this comparison is the volumetric resistance coefficient, or $\frac{R}{\frac{\rho}{2} \nabla^{2/3} v^2} = C_t \nabla$ where R is the total resistance in pounds, ρ is the mass density of water, ∇ is the displacement in cubic feet, and v is the velocity in feet per second. Values of this coefficient versus the Froude Number $\frac{v}{\sqrt{gL}}$ are plotted in Figure 14 for the barges tested.

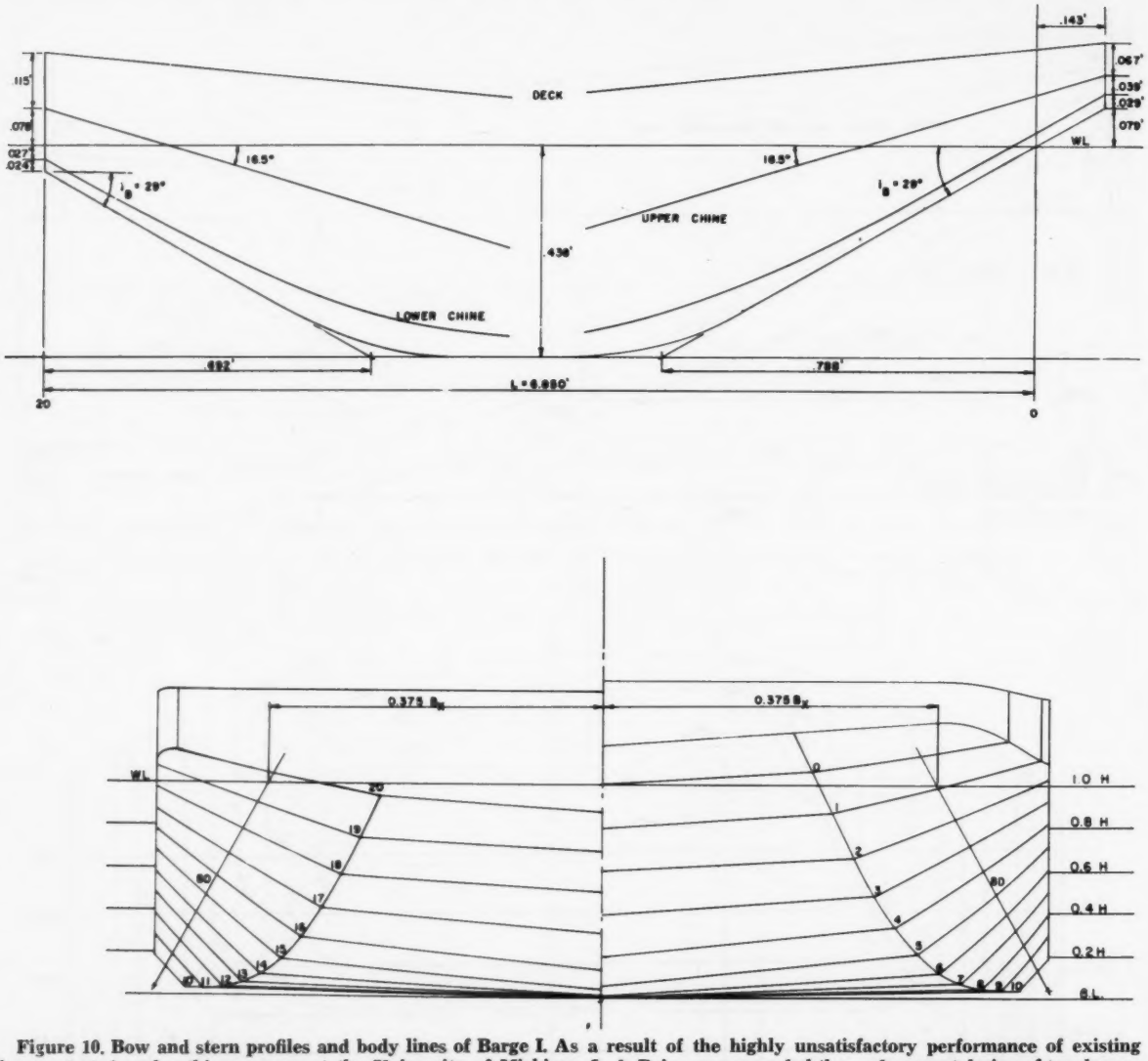

Figure 10. Bow and stern profiles and body lines of Barge I. As a result of the highly unsatisfactory performance of existing barges tested under this program at the University of Michigan, L. A. Baier recommended the replacement design of two barges using simplified, straight-element construction. This 112′x30′x7′ was designed by him as a replacement for Barge E and another barge of similar dimensions.

For purposes of single number comparison the average value of the volumetric resistance coefficient between Froude Numbers of 0.10 and 0.20 can be used. These values are given in Table II.

TABLE II

Barge	$10^3 C_t \nabla$
A	23.9
B-1	45.1
B-2	38.2
C	40.3
D	64.0
E	77.4
F	68.8
G	30.3
H	57.9
I	33.3
J	39.6

Earlier it was stated that the sectional area curve gives a positive clue of potential barge performance. The sectional area curves of the eleven barges tested are given in Figure 15. It should be noted that Barges G and H were fitted with yaw-correcting skegs during these tests.

As a general rule the length of entrance and run is an important factor in determining barge resistance. The barges with greater rake end lengths are usually less resistive than those with the shorter rake end lengths. The differences in Barge A, the best of the group, and Barge E, the worst of the group, are obvious in this respect.

There are some contradictions to this general rule which are evident. Barge D with the shortest entrance and run is superior to Barge E. Examination

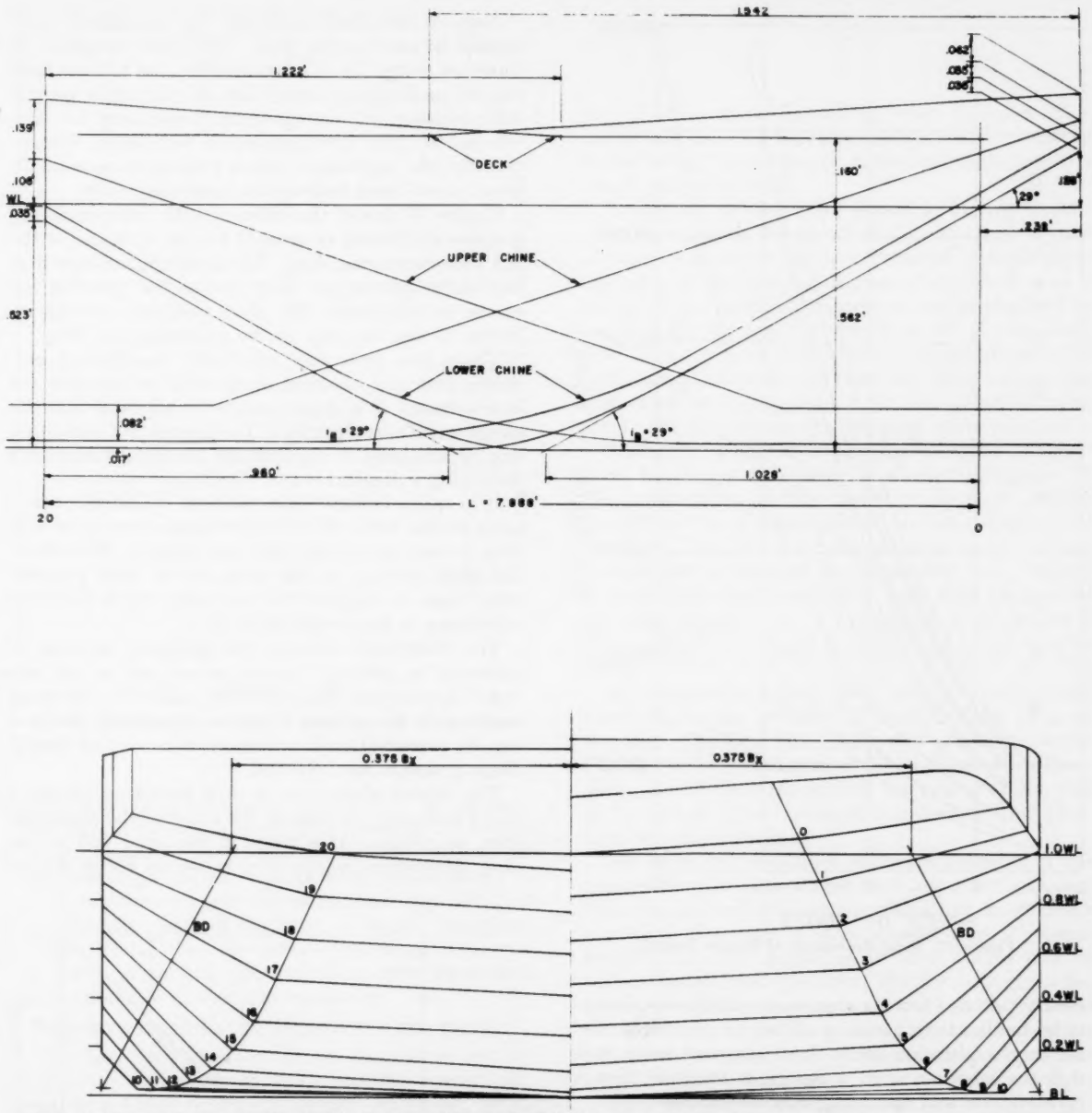

Figure 11. Bow and stern profiles and body lines of Barge J. This barge was designed by L. A. Baier as a replacement for the obsolescent types of 130′ barges tested. It is a straight-element form 130′x35′x9′.

of the sectional area curves indicates a part of the reason for this superiority. The design of Barge E was such that the sectional area curve attains an infinite curvature at the points where the rake ends join the parallel middlebody, thus causing excessive acceleration of the flow in these regions leading to high resistance. In addition, the fenders which were placed oblique to the flow lines on this design contribute to its high resistance.

Fairness of load waterline is also an important factor. The rectangular waterlines of Barges D and F and the infinite curvature in the waterline of Barge E place them in the high resistance category.

The differences between Barges I and J are more difficult to explain since their waterline and sectional area curves are almost identical, as is their general design configuration. It appears that either the greater cross sectional area or the greater displacement length ratio of Barge J explains its higher resistance.

The complicated rake end design of Barge C was apparently not justified since it was inferior in performance to the "straight-element" designs, Barges I and J. The long, ship-shape bow of Barge A is evi-

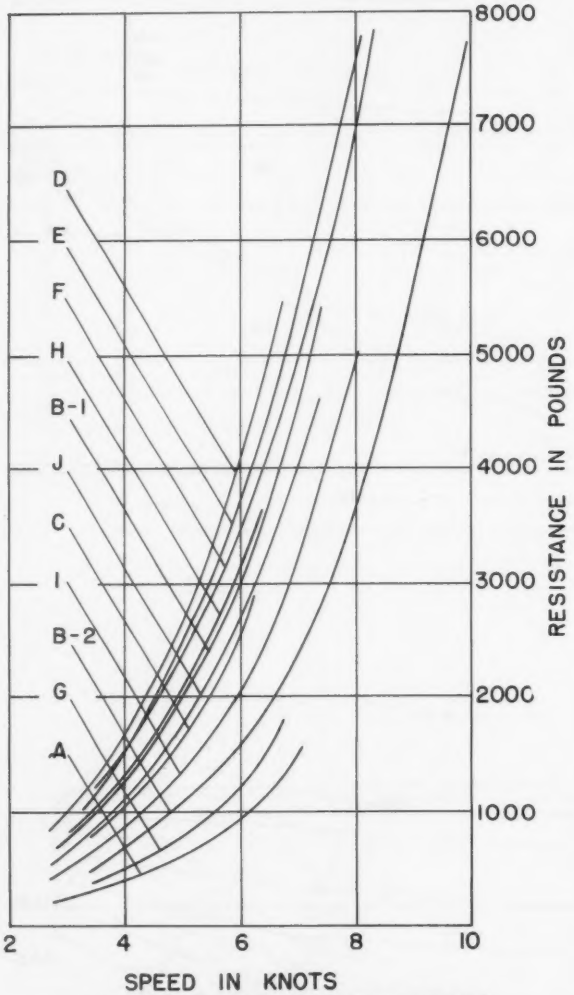

Figure 12. Total Resistance of Barges Tested.

dently justified from a resistance standpoint since it is by far the least resistive of the barges tested. Yet for any application other than seagoing tows, it is dubious whether such a design is feasible from a construction and operating cost standpoint.

Practically it appears that Barges B, G, H, I, and J incorporate the best design principles for river and harbor barges. Barge A appears as a desirable design for deep sea towing.

SKEG DESIGN AND PERFORMANCE

The three general categories of skegs tested are shown in Figure 16. These may be referred to as pyramid-type skegs, plate skegs with prisms, and angled-plate-type skegs. The pyramid-type skegs were designed and patented by the Ingalls Shipbuilding Corporation. The plate skegs with prisms are a design evolved by the Experimental Towing Tank. The angled-plate-type skegs were developed for the Dravo Corporation by Professor L. A. Baier.

Each of the skegs designed was completely successful in overcoming yaw (with the exception of those on Barge D). Unfortunately, due to time limitation, each design could not be varied to permit determination of the optimum dimensions for correction of yaw with minimum resistance. Consequently, the discussion which follows is necessarily based upon those tests which were conducted.

Figure 17 shows the difference in volumetric resistance coefficient of several barges with and without yaw-correcting skegs. These curves indicate that the angled-plate-type skeg causes the greatest increase in resistance. The plate skeg with prisms on Barge A was superior to the pyramid-type skeg.

These few tests are admittedly insufficient evidence that any of these skegs will be superior for every design. It is quite possible in all cases that the skegs were over designed. Yet the results presented can be analyzed in light of the previous statements regarding enhancement of directional stability.

It is quite evident that addition of lateral resistance aft has little effect on yaw since transverse motion in yaw is of relatively low velocity. Therefore, the plate portion of the skeg serves little purpose other than to support the member which provides resistance to the longitudinal flow.

The maximum effect of the dragging member is achieved by placing it as far astern and as far outboard as possible. This gives the maximum restoring moment to the yawing barge or conversely the yaw can be corrected with a minimum amount of drag if these precepts are followed.

The angled-plate-type of skeg tested on Barges I and J redirects the flow at the angle of the plate and then separation takes place at the after end of the skeg. The pyramid-type skeg tested on Barge A pro-

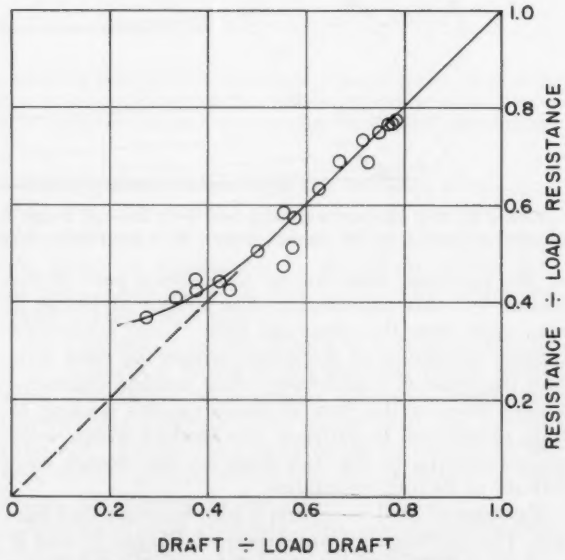

Figure 13. Effect of Draft on Resistance.

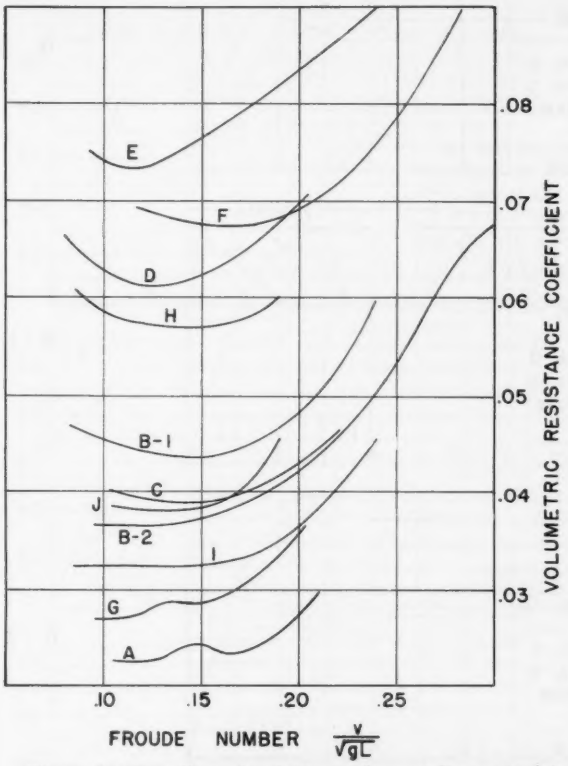

Figure 14. Non-dimensional Comparison of Barge Resistances.

vides increasing resistance to the flow by successively larger pyramids as the flow moves aft. Both the double prism on the single plate skeg on Barge B and the single prism on double skegs on Barge A cause separation, and therefore maximum drag at the aftermost part of the skeg. It would, therefore, appear logical that the prism-type skegs employed on Barge A should give maximum yaw correction with minimum increase in resistance.

RECOMMENDATIONS FOR BARGE HULL FORM DESIGN

The tests conducted under this study alone are not sufficiently definitive to draw specific conclusions regarding barge hull form design. However, when the results of these tests are added to the knowledge gained in other barge model studies, it is possible to derive some general recommendations for barge design.

A rounded bilge barge will generally have a slightly lower resistance than a "straight-element" form. Its construction cost will be higher but its maintenance will be slightly less.

Figure 18 delineates the lines development recommended for barges with rounded bilges and formed rake ends. It is assumed that the length, beam, and draft will be determined by economic and operational factors. Thus, attempts to lower resistance must be confined to the proportioning and shaping of rake ends. In dealing with rounded bilge forms, the use of a constant radius simplifies fitting by reducing the rolling or furnacing operation to a single pair of strakes.

Two types of barges are shown in Figure 18. The rake end profiles are identical. In one barge a good sectional area curve has been obtained by tapering in the sides to the headlog. Where a large deck area is required, the sectional area curve can be retained by varying the deadrise as shown in the second body plan. The fore and after rakes are symmetrical with 15% being cut from the rake aft. This feature has the added advantage that if flotilla operation is desired, the barges may be secured stern to stern.

As another alternative type, the "straight-element" form for barge rake ends is shown in Figure 19. The proportions shown represent optimum values established by a series of tests at the University of Michigan. This form is adaptable to the use of developed plates between the upper and lower chines. A conical development can be used with the apex of the cone at point "A." A cylindrical development is also possible or straight elements, as shown, may be used.

As previously stated, yaw may be successfully overcome by the addition of drag inducing skegs at the stern. The twin plate skegs with prisms shown in Figure 16 are recommended for this purpose. These skegs should be so placed that the prisms are located as far aft and as far outboard as possible within practical design limitations.

The bare hull resistance of barges designed in this manner cannot be predicted with any great accuracy from the limited amount of model test information available. However, it does appear that a general formula for the resistance of such forms can be approximated from the data. The formula given below assumes that the resistance varies with the cross sectional area of the barge and that the shape of the resistance curve relative to displacement is similar for all barges of this type.

The following symbols are used:

R=resistance of barge in pounds
v=speed of barge in feet per second
g=acceleration of gravity in feet per second squared
L=waterline length of barge in feet
A=cross section area of underwater body of barge in square feet
∇=underwater volume of barge in cubic feet
S=wetted surface of barge in square feet
C_f=Schoenherr frictional resistance coefficient

The total resistance of the barge for any speed is then given by the formula:

$$R=Sv^2(C_f+0.0004)+10^{-3}(0.18A+K)\nabla^{2/3}v^2$$

where K is derived from Table III

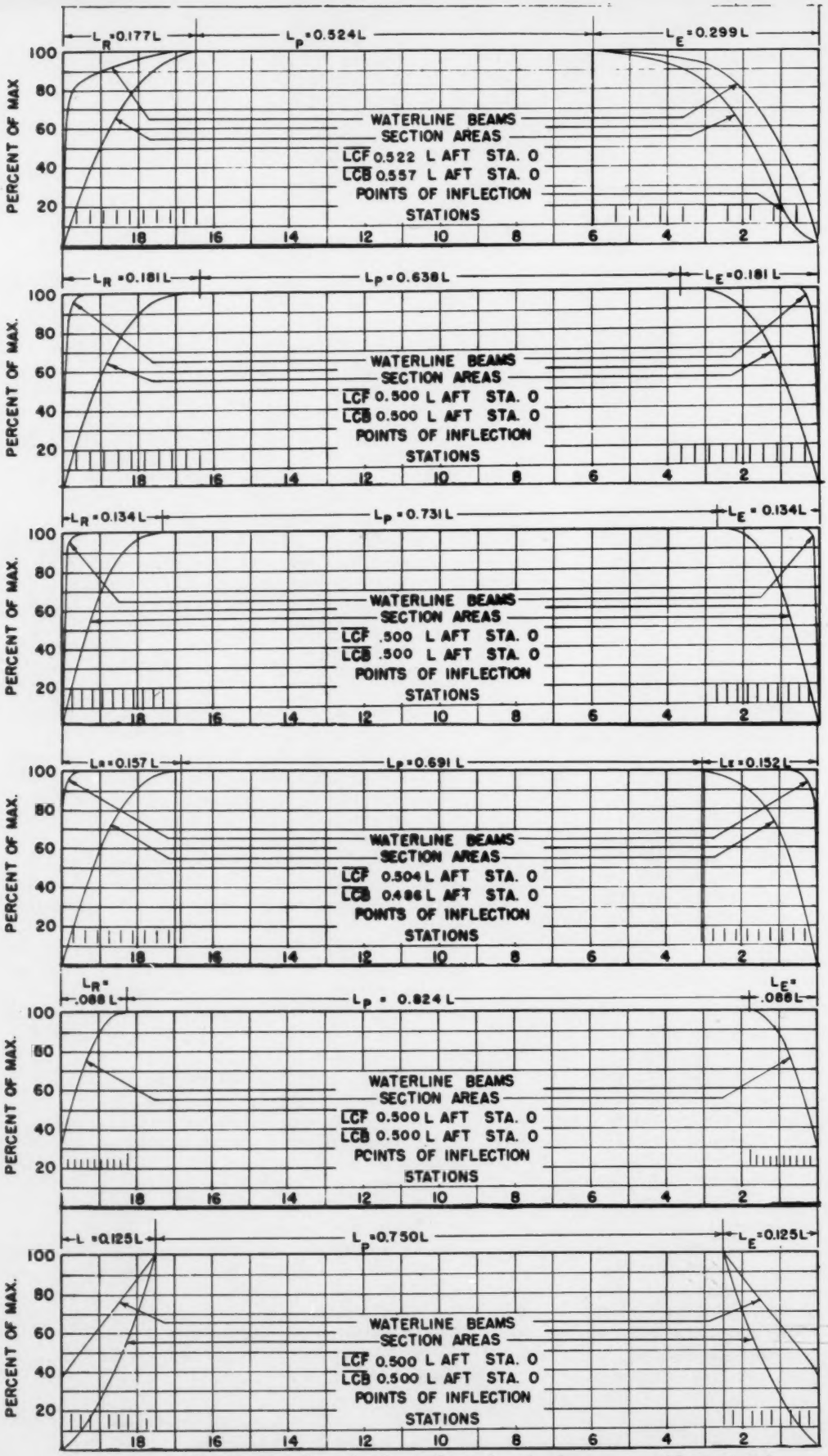

Figure 15. Non-dimensional waterline and sectional area curves of barges tested.

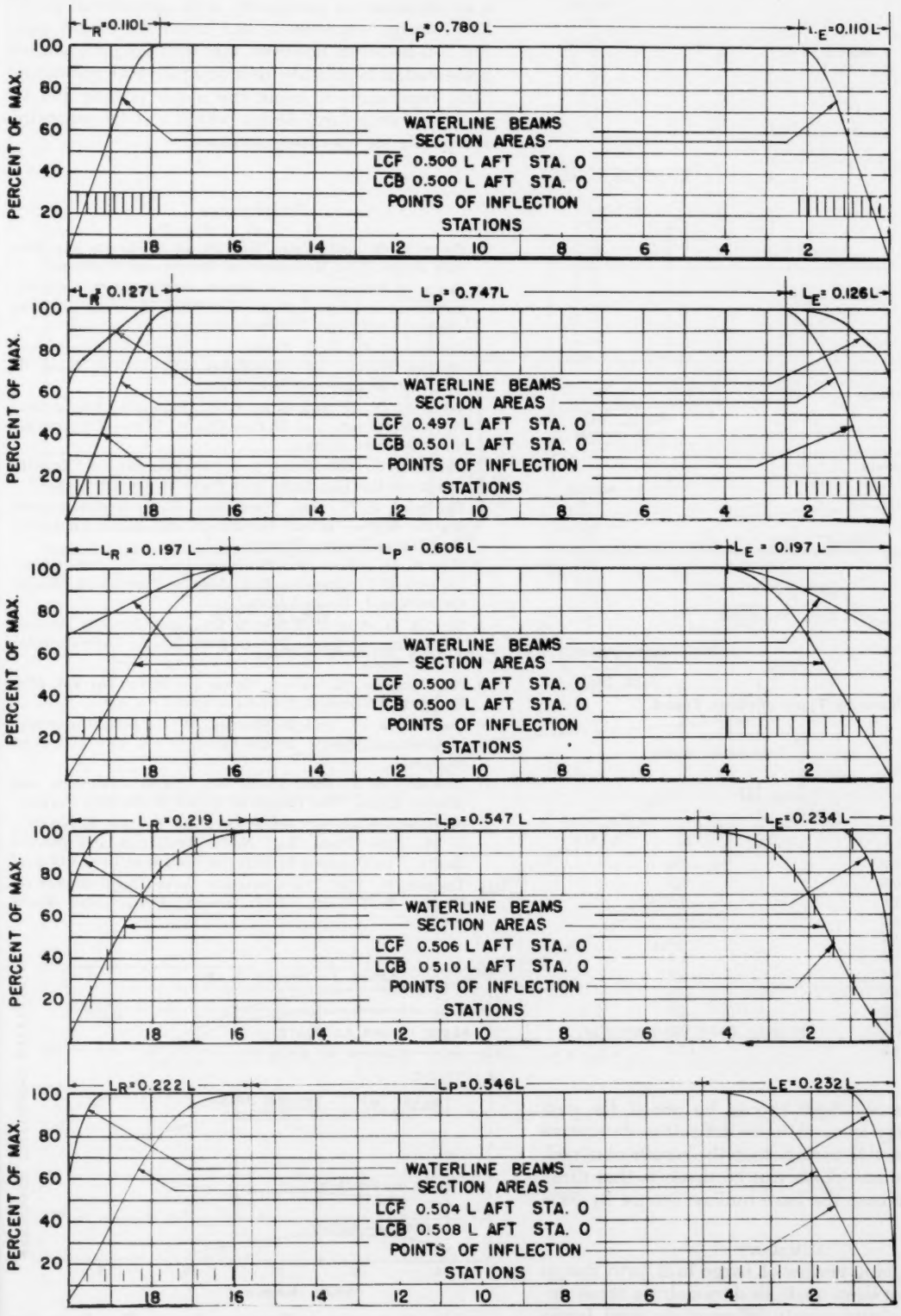

Figure 15 Continued.

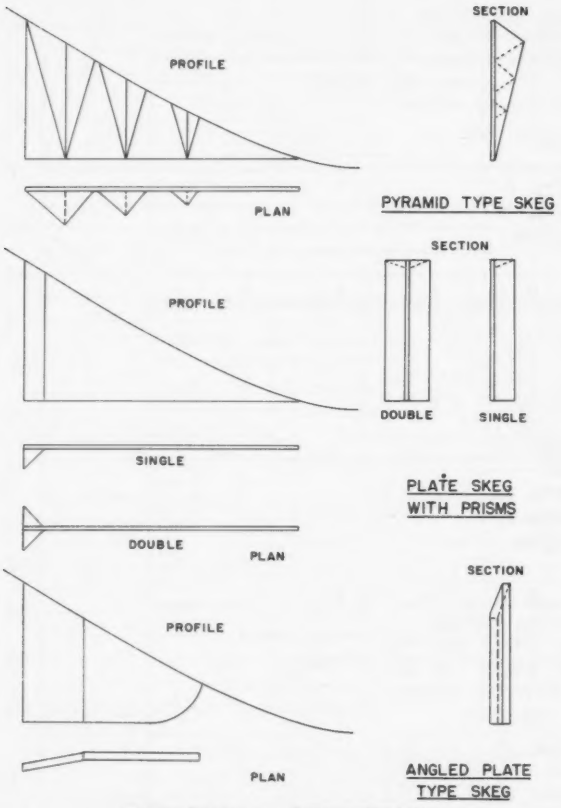

Figure 16. Types of Skegs Tested.

TABLE III

$\frac{V}{\sqrt{gL}}$	K
0.6	−7.6
0.8	−8.9
1.0	−9.5
1.2	−10.1
1.4	−9.8
1.6	−7.9
1.8	−4.6
2.0	−0.8
2.2	+2.6
2.4	+6.2
2.6	+12.4

The resistance which should be added for yaw correcting skegs is much more difficult to determine because of the wide variations in the results obtained. The best estimate which can be made is that these skegs will increase the bare hull resistance by 50% to 100%.

SUMMARY

In the foregoing review of barge hull form design an attempt has been made to demonstrate those design characteristics which differentiate good forms from bad forms. Successful barge design requires a combination of familiarity with operational problems, design experience, and extensive model testing. It is believed, however, that with the information presented, it is possible for a designer with relatively little experience to avoid the major pitfalls and to evolve a barge form design which will be generally acceptable for operating service.

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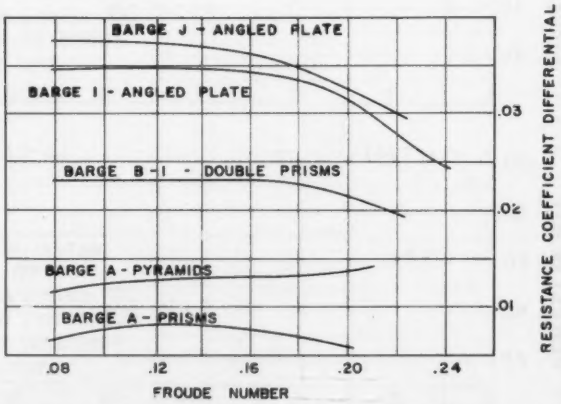


Figure 17. Increase in Resistance Due to Yaw Correcting Skegs.

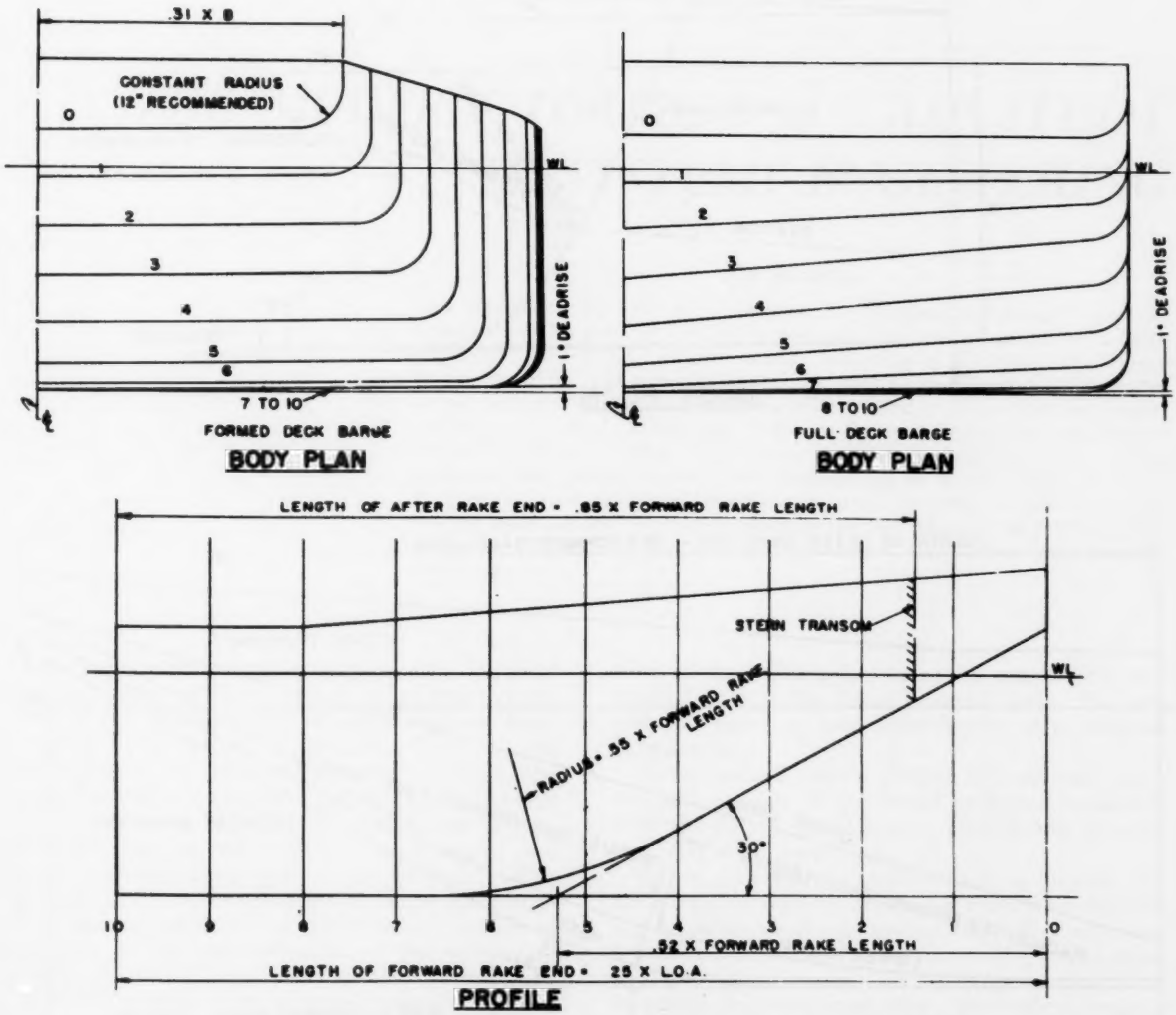
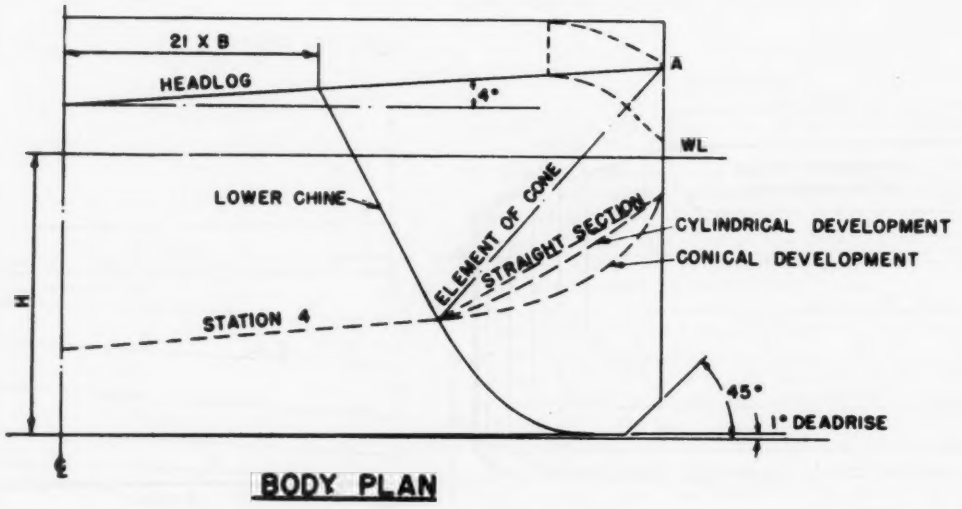


Figure 18. Recommended lines development for barges with formed rake ends.



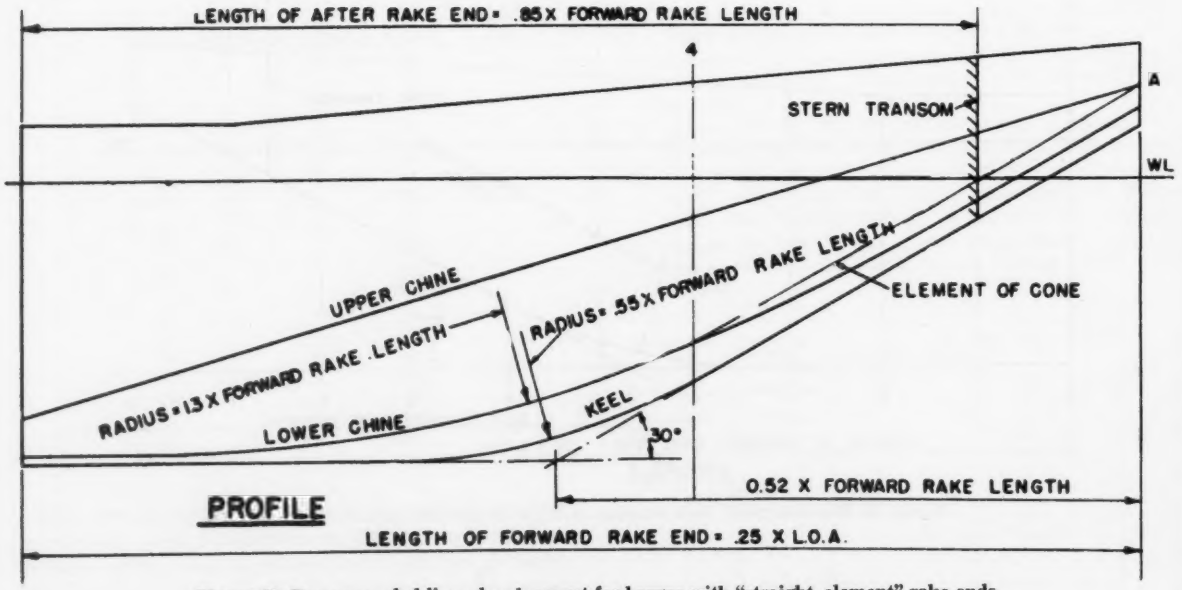


Figure 19. Recommended lines development for barges with "straight-element" rake ends.

GILFORD G. QUARLES

THE MODERN TORPEDO: A CASE STUDY IN SYSTEMS ENGINEERING

THE AUTHOR

born December 24, 1909 in Charlottesville, Virginia. Graduated from the University of Virginia with a B.S. in electrical engineering in 1930 and Ph.D. in physics, 1934. Taught physics at the University of Alabama and Furman University until 1944 when he joined the staff of the Harvard Underwater Sound Laboratory. At the end of the War, moved to Penn State as project engineer in the newly established Ordnance Research Laboratory and became Assistant Director in 1947 and Director in 1952. In these capacities, he has conducted and guided research and development in various fields related to the Navy's torpedo program, including acoustics, electronics, hydrodynamics, homing systems, control and propulsion. He is a member of AIEE, ASEE, American Physical Society, American Ordnance Association, Tau Beta Pi, and Sigma Xi.

ALTHOUGH THERMONUCLEAR weapons have captured the imagination of the public at large, the torpedo remains the Navy's most effective weapon. Rear Admiral Frederick S. Withington, Chief of the Navy's Bureau of Ordnance, recently said that "the most effective way to sink a ship is to hole the hull and let salt water flow in. The surest way to produce that hole is still with our most potent and feared weapons, the torpedo and the mine." The fact that the Navy concentrates a large percentage of its annual research and development budget on torpedoes is but one indication of the continuing importance of the torpedo among naval ordnance.

Today's torpedo is an extremely complex device. It is a self-guided missile that must seek out, track down, overtake and destroy an enemy ship or submarine, while ignoring many distracting influences. Knowledge and skills in almost every discipline of the physical sciences and engineering are used in its design. Since the torpedo is an underwater guided missile (torpedoes, incidentally, were the *first* guided missiles), the application of hydrodynamics is fairly obvious. Perhaps less obvious, torpedo research and development also involve electronics, aerodynamics, acoustics, mechanics, mathematics, and even other disciplines. And the contributions of each of these disciplines must be coordinated and applied in a well-ordered systems sense. The torpedo, as much as any other device, is a study in compromises.

To understand this complexity, it is necessary only to look at a few of the broad problems associated with the design, development, engineering, production, and use of torpedoes.

As an underwater guided missile, a torpedo is a self-propelled and self-controlled vehicle for delivering an explosive charge against the hull of a surface or subsurface vessel. No human intelligence is available to make decisions for the torpedo after it is launched. In a very real sense, the modern torpedo is an explosive-laden, self-destructing submarine that is driven against the target by intelligence, propulsion, and control systems incorporated in its design.

In size, modern torpedoes range from about 12 inches in diameter, six feet in length, and 500 pounds in weight to a diameter of about 22 inches, a length of around 25 feet, and a weight of about 4,000 pounds. The weight of the explosive varies from about 50 to 800 or even 1,000 pounds. Its speed varies from 15 to 45 knots, and ranges of about 10,000 yards have been achieved.

Torpedoes must be designed for attacks against targets as varied as a five-knot freighter, a 30-knot troop transport, snorkeling submarines with speeds of perhaps 20 knots that are capable of evasion in three dimensions, battleships, aircraft carriers, cruisers, and many smaller and possibly faster escort vessels. Each type of target imposes definite requirements on the torpedo. The torpedo for tracking down and destroying a high-speed, deep-draft capital ship might be completely ineffective against slow, shallow-draft freighters. Certainly, a torpedo designed for a target confined to the surface cannot be expected to attack a submerged target successfully.

To complicate the problem further, torpedoes for use against these targets must be capable of being launched from a submerged submarine, several types of surface vessels, and aircraft. Each of these launchers imposes definite problems, requirements, and restrictions on the torpedo design. For instance, a torpedo for submarine launching must be designed to withstand pressure of perhaps more than 500 pounds per square inch and must be capable of propelling and controlling itself in both deep and shallow water. To be launched successfully from an airplane traveling at 200 to 250 miles an hour, a torpedo must withstand water-entry shocks as high as 250 to 300 times the acceleration of gravity. If it does not enter the water at exactly the right angle, it may be shattered into dozens of pieces. It must be both aerodynamically and hydrodynamically stable, or it must be modified for proper air-flight characteristics by the additions of appendages that can be discarded upon entering the water. Even the seemingly simple surface launching causes design headaches. A torpedo capable of being launched successfully at 250 miles an hour from an airplane may not be capable of being launched from a deck-mounted tube only 15 or 20 feet above the surface of the water because of the difference of the water-entry angle. After all, 1,000 inert pounds dropped from a height of 15 feet creates quite a wallop.

Further, the accuracy of the attack is limited by the accuracy of the information about the target. This fact, complicated by the development of radar, which significantly lengthens the safe-approach range of the launcher, also imposes restrictions on torpedo design.

Another general problem of major significance involves logistics. Not only must the torpedo be transported to an advanced base, but often must be carried aboard the launching vessel for perhaps several weeks before it is fired. Consequently, size, weight, and shape are extremely important design factors, especially with submarines and the smaller launching vessels. Size and weight also depends on the intended use of the torpedo. The modern capital ship cannot be destroyed with a small explosive charge, and it is neither efficient nor economically sound to use a major piece of ordnance to destroy small escort craft. A man must be sent to do a man's work, but it is foolish to appropriate a man's time and strength to do a boy's work.

The torpedo, then, must be designed as a system to perform a specific purpose. The characteristics of this system must be determined by the intended and possible alternative tactical situations (including targets, launching craft, operating conditions, and the like), as well as space, weight, transportation, cost, shelf life, obsolescence, and other considerations. This interdependence is met by over-all systems engineering.

The actual design of a specific weapon must start somewhere. The basic characteristics usually employed as a starting point are speed, range, and type of control.

Since the torpedo must overtake its quarry to destroy it, the speed designed into the torpedo must be largely determined by the speed of the intended target. Another aspect, however, is that the speed controls flight time; the faster the torpedo, the less time the target has for evasive action.

The minimum running range is indicated by the tactical situation. Generally speaking, it is determined by the minimum safe-approach distance of the launcher to the target. Other factors include the speed of the closure during a stern chase and the possibility of reattacks if the torpedo misses on the first attack. For the second of these, range is related to target speed and the circumference of the torpedo's turning circle.

Almost every torpedo must be controlled in both depth and course. This control is usually achieved through rudders and elevators that deflect in response to some type of error signal or other command originating within the torpedo. The simplest system is for "straight runners," which swim at a fixed depth in a straight line controlled by a gyroscope mechanism. More sophisticated types incorporate various maneuvering controls under either self or external guidance. In some of these, the maneuvering pattern is present; in others, it is determined by information from either the target or the launching vessel during the chase.

Regardless of where he starts his design, the torpedo engineer must always bear in mind the general requirements of reliability, productibility, serviceability, and economy, listed in order of their probable importance. No matter how elaborate and elite the performance of the experimental models, the torpedo may actually be a liability if it fails to produce a hit in a critical engagement. If it cannot be produced in quantity, it will never be an effective fleet weapon. If it cannot be serviced under field conditions, its usefulness will be seriously limited. Finally, cost of production is always important, despite the fact that the cost of getting the torpedo from storage to the target may be many times greater than the cost of producing it in the first place.

How are these design factors interrelated in the actual designing? Let's look at a few examples.

One of the most direct and specifically definable

relations is that between speed and running range. This relationship is determined basically by energy considerations: the faster the torpedo runs, the more power must be supplied because of the increased drag; and the farther the torpedo runs, the greater the distance through which the propulsive force must be exerted. These considerations determine the compromise between the desired speed and the desired range.

Speed, however, is also related to noise generated by the torpedo. The faster a torpedo runs, the noisier it is, not only because the power plant must be larger but also because of noisy cavitation, which is caused by bubbles of water vapor formed by the reduction of pressure as the water flows past the torpedo. Cavitation is also related, through pressure, to depth; and speed, range and depth are interrelated in the problem of obtaining the best operational characteristics. Noise is most important in that it determines the range at which a target can detect the torpedo and, for an acoustic torpedo, obscures the target signal and hence decreases the homing sensitivity.

The relationship between power and energy has yet another significant aspect. The speed at which the torpedo runs, together with its hydrodynamic characteristics and the desired running range, determines the energy that must be expanded. The total energy, in combination with the efficiency of the power plant, governs the amount of fuel needed. This amount, in turn, determines the size of the fuel compartment or is determined by the allowable space and weight for fuel storage. In any event, some compromise is involved.

The size of the power plant depends on the rate at which the energy must be expended. If the torpedo is a slow runner, only a relatively small motor will be needed; if it is to be used against fast targets, a larger plant must be incorporated in the design. Generally speaking, the engineer can employ a small plant, as measured by ordinary standards, since the total operating life of a torpedo is at most a very few hours. For example, an electric motor to deliver 100 horsepower in a torpedo may be smaller than an ordinary five-horsepower commercial motor.

The basic size of the torpedo is a compromise among several considerations: the amount of explosive needed to do the job; power and energy requirements; space, weight, and buoyancy factors; and the characteristics of the launching vessel. The buoyancy of the torpedo and, consequently, its ability to maintain depth are determined by the ratio of over-all volume to total weight, since the average density of the torpedo can be only slightly different from the density of the sea water in which it must swim. The volume-weight ratio is fixed within narrow limits. This fact imposes severe restrictions on space and weight relationships. To cram as much explosive as possible into the available space, every component must be as small and as light as engineering skill can make it without violating efficiency and reliability.

Compromises such as these are realized in the design of specific components. Each component must be designed to integrate with the others to form an operational system that will function effectively in an even larger system consisting of the launching vessel, the torpedo, and the target. This system, in turn, is only a part of a still larger system that involves not only an entire operation with several different types of launchers and targets but also the production, proofing, testing, storage, servicing, and logistics of the torpedo.

The engineer who designs such a torpedo must be aware of all these problems and must have sufficient training in a wide variety of technical disciplines to understand the interrelationships among the many design factors. Even service and operating personnel in the field must be at least aware of these factors to avoid or to eliminate possible sources of malperformance. The torpedo has only one chance; when it is fired, it must do its job.

Let's look broadly at some of this variety.

Mechanical engineering skills are involved in the design of the propulsors and the nonelectric prime movers (turbines and engines), the non-electric control mechanisms and many features of the electrical ones, the mechanical linkages between the control motor and the external control surfaces, and the frequently used air-driven steering engines. The entire maneuvering control mechanism of the torpedo—the gyro and the depth-control devices—are strictly the mechanical engineer's responsibility. The terrific launching shock imposes severe restrictions on mechanical design; and the problem of vibration, especially in its effect on delicate sensing, computing, and control mechanisms, is a tough one to solve in any torpedo.

Torpedo applications of gyro mechanisms, incidentally, impose design restrictions not encountered in other gyro applications. For use in a torpedo, the gyro must be spun up in a fixed position and released very quickly, since both the launching vessel and the target are moving and the course of the torpedo cannot be fixed until a fraction of a second before it is launched. In a typical application, the wheel is spun by an air blast and then maintained at a constant speed by an air stream of a lower pressure. Specifications call for the gyro to reach its operating speed of 20,000 revolutions per minute and be uncaged in 60 revolutions. This is a terrific mechanical engineering problem.

The electrical engineering problems are perhaps more obvious than the mechanical. Electrical propulsion, electrical rudder and elevator control, and the electronic system of the typical intelligence mechanism are, of course, electrical engineering problems. The problems involved in this area are quite different in torpedo applications from those in other applications: the minimum weight and space requirements, together with the short running life, long shelf life, and extreme variations in tempera-

ture during storage, impose very special requirements.

The hydrodynamicist is concerned with body design for proper drag, stability and the like; with maximum efficiency of propulsion with the least possible amount of unwanted noise; with the design of the control surfaces; and with the determination of the control constants of the body. A very special and particularly difficult problem occurs with the torpedo designed for air drops. When the torpedo enters the water at high speed, it carries with it a bubble of air that prevents it from touching the water except at its nose for an appreciable period of time. This fact creates a difficult problem in control, especially since the torpedo must enter the water at an angle small enough to permit it to be dropped in shallow, as well as in deep, water.

The acoustician is one of the most important members of the research and design team for modern torpedoes, since the torpedo is detected primarily by acoustic means and since many modern torpedoes are acoustically controlled. The first of these means that the noise produced by the torpedo must be reduced as far as possible to increase the stealth with which it tracks its quarry and, consequently, to decrease the time the target has for evasive action. The second means the development of an effective, sensitive listening system, the output of which can be coupled successfully to an accurate control system. It also means that self-noise must be controlled or minimized to keep it from interfering with the listening system, just as machinery noise interferes with a conversation in a noisy machine shop. In addition, since the noise from the target is transmitted by the sea medium, it is necessary that the design of the torpedo be based upon exact knowledge of the behavior of sound in the ocean. This is an area in which much work still needs to be done. It is known, for instance, that the surface and bottom reflect and scatter sound in such a fashion that the noise heard by the torpedo often does not come from the direction in which the target actually lies. These problems demand the application of a high degree of acoustic skill.

Upon the mathematician or mathematical engineer falls the problem of achieving optimum performance with a minimum number of false steps. Analytical processes must be employed at every stage of design and development. The most significant role, however, that the mathematician or mathematical engineer can play is that of determining by analytical means the interrelationships among the various components of the torpedo and between the torpedo and the other components of the next higher system.

The contributions of these separate disciplines must be subordinated to over-all system effectiveness in a particular situation, just as the particular skills of the separate members of a football team must be integrated with those of the other members and with the particular characteristics of the opposing teams to fashion a winning season. The modern torpedo cannot tolerate "stars." The effectiveness of the most sensitive listening system may be completely voided by an improperly designed data-processing system; maximum stability characteristics may result in a turning radius that makes it impossible for the torpedo to follow its quarry; the propeller that produces the most thrust per unit of power input may produce so much noise the torpedo can't hear itself think.

The torpedo then is a relatively small underwater guided missile that is born in compromise and ends as a prime example of the value—even the necessity—of systems engineering. Probably nowhere is there a better example of the effectiveness of cooperation among scientists and engineers in such a wide range of disciplines.

The recently commissioned aircraft carrier "Saratoga" is the second such ship to be equipped with a TACAN (tactical air navigation) system and with a long-range, ultra-high frequency radio system.

MERL D. CREECH
JAMES I. McPHERSON
ROBERT L. AMMONS

A METHOD OF LOCATING THE NODAL POINTS IN UNDAMPED TORSIONAL VIBRATION PROBLEMS

Merl D. Creech was born in Kansas, 1903, attended the University of Oklahoma 1924–1930; received the degree of B.S. in Mechanical Engineering 1929 and M.S. in Engineering in 1930; instructor University of Tulsa 1931; Engineer Black, Sivalls & Bryson, Oklahoma City, Oklahoma, 1936–1940; Plant Engineer Dravo Corp., Chicago, Ill., 1941; Professor of Mechanics, University of Oklahoma, 1941–1955; Associate Professor Mechanical Engineering, New Mexico College of A. & M.A. since September 1955. Member A.S.M.E., I.A.S., Sigma Xi, Tau Beta Pi, Pi Tau Sigma, Sigma Tau; has patents on Laminated Pressure Vessel Construction; was consultant on Project Loki, Eclipse Pioneer Div. Bendix Aviation Corp., Teterboro, N.J.; made Flutter Analysis of latest modification of Aero Commander for Aero Design Engineering Co., Oklahoma City, Okla.

James I. McPherson was born in Pennsylvania, 1931, attended the University of Oklahoma 1948–1952; received the degree of B.S. of Mechanical Engineering in 1952; served as Radar Officer on the USS Toledo (CA-133) from 1953–1954; holds reserve commission of Lieutenant (Junior Grade) USNR-R; graduate work, 1954–1955, Univerity of Oklahoma; graduate work since 1955, New Mexico College of A. & M.A.; instructor of Mechanical Engineering, New Mexico College of A. & M.A., since September 1955; member A.S.M.E., Tau Beta Pi, Pi Tau Sigma, Sigma Tau, Phi Eta Sigma.

Robert L. Ammons was born in California, 1934; attended Ventura College, 1952–1954; attending New Mexico College of A. & M.A.; Laboratory Assistant, Mechanical Engineering Department, New Mexico College of A. & M.A.; presented paper, Automatic Guidance Systems, Rocky Mountain Tier, Region VIII, A.S.M.E.; member A.S.M.E., American Rocket Society.

In the August 1949 Journal of the American Society of Naval Engineers, a method of determining the natural frequencies in an undamped torsional vibration system was presented. A rather simple extension of equation (2) in appendix A, page 592, of this paper gives a general method of locating the nodes of a multi-mass undamped torsional system.

A multi-mass system is schematically shown in figure 1.

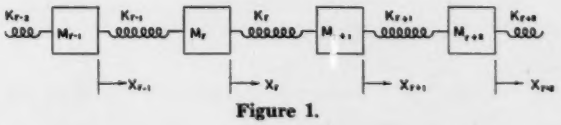


Figure 1.

In figure 1 each of the masses is given a displacement x to the right. Note: that although figure 1 shows a multi-mass translation system, for a torsional

system it is only necessary to let the displacement x be an angular displacement in radians.

From reference (1) we can write:

$$(\text{Force})_r = M_r x_r \omega^2 \qquad (1)$$

Where ω is the natural frequency for which it is desired to calculate the nodes.

Assume

$$x_1 < \ldots\ldots x_{r-1} < x_r < x_{r+1} < \ldots\ldots x_{n+1} \qquad (2)$$

In equation (3) in appendix of reference (1) the force in the r^{th} elastance is

$$k_r(x_{r+1} - x_r) \qquad (3)$$

Likewise the force in the $(r-1)^{th}$ elastance is

$$k_{r-1}(x_r - x_{r-1}) \qquad (4)$$

The forces acting on the r^{th} mass are

$$(F_{r-1} - F_r) = k_{r-1}(x_r - x_{r-1}) - k_r(x_{r+1} - x_r) \qquad (5)$$

Substituting the forces from equation (5) into equation (1) we get

$$k_{r-1}(x_r - x_{r-1}) - K_r(x_{r+1} - x_r) = M_r x_r \omega^2 \qquad (6)$$

Equation (6) can be rearranged to give

$$x_{r+1} = 1 + \frac{k_{r-1}}{k_r} - \frac{I_r}{k_r}(\omega^2) \quad x_r - \frac{k_{r-1}}{k_r} x_{r-1} \qquad (7)$$

Since in a multi-mass system the number of natural frequencies is one less than the number of masses, we will introduce a superscript to designate which harmonic frequency is being used. The superscript should not be confused with an exponent.

In reference (1) the frequency equation derived was written in terms of u, where u was equal to $-\omega^2$.

Introducing u and the superscript n into equation (7), we have

$$x^n{}_{r+1} = 1 + \frac{k_{r-1}}{k_r} + \frac{I_r}{k_r} u^n x^n{}_r - \frac{k_{r-1}}{k_r} x^n{}_{r-1} \qquad (8)$$

Now let

$$Q^n{}_r = 1 + \frac{k_{r-1}}{k_r} + \frac{I_r}{k_r} u^n \qquad (9)$$

From this we can write

$$x^n{}_{r+1} = Q^n{}_r x^n{}_r - \frac{k_{r-1}}{k_r} x^n{}_{r-1} \qquad (10)$$

This is the general equation for the determination of the deflection of the r^{th} mass for a system vibrating with the n^{th} harmonic frequency.

This will be illustrated for the numerical example given in reference (1).

NUMERICAL EXAMPLE

Suppose we have a four cylinder engine and flywheel

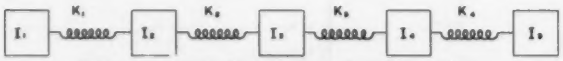


Figure 2. Equivalent 5 mass, 4 spring system.

The constants of the system are as follows

$I_1 = 10$ slug ft^2

$I_2 = I_3 = I_4 = I_5 = 0.10$ slug ft^2

$k_1 = 1.3\ (10^6)$ lb-ft/radian

$k_2 = k_3 = k_4 = 1.5\ (10^6)$ lb-ft/radian

The frequency equation for the equivalent five mass, four spring system, as given by reference (1), is

$$u^4 + 103.44499\,(10^6)\,u^3 + 3246.1499\,(10^{12})\,u^2 + 31342.50107\,(10^{18})\,u + 45630.0015\,(10^{24}) = 0$$

The roots of the frequency equation, as given by reference (1), are

$u^I = -52.643\,(10^6)$ rad/sec^2

$u^{II} = -34.383\,(10^6)$ rad/sec^2

$u^{III} = -14.347\,(10^6)$ rad/sec^2

$u^{IV} = -1.757\,(10^6)$ rad/sec^2

From equation (9), it is a relatively simple matter to construct a table of values for $Q^n{}_r$. (Table A)

$$\frac{k_1}{k_2} = 0.86666 \qquad \frac{k_2}{k_3} = \frac{k_3}{k_4} = 1.0000$$

$$\frac{I_1}{k_1} = 7.69230\ (10^{-6})\ \text{sec}^2$$

$$\frac{I_2}{k_2} = \frac{I_3}{k_3} = \frac{I_4}{k_4} = 0.06666\ (10^{-6})\ \text{sec}^2$$

TABLE A

Table of values for $Q^n{}_r$

$\downarrow n$ \ $\rightarrow r$	1	2	3	4
I	−403.94575	−1.64253	−1.50918	−1.50918
II	−263.48435	−0.42531	−0.29127	−0.29127
III	−109.36143	+0.91029	+1.04363	+1.04363
IV	− 12.51537	+1.74954	+1.88288	+1.88288

Using equation (10) the relative amplitudes of masses are found.

$$x^n{}_{r+1} = Q^n{}_r x^n{}_r - \frac{k_{r-1}}{k_r} x^n{}_{r-1}$$

Since these are relative amplitudes, the amplitude of any mass may be given any arbitrary value and the amplitudes of the remaining masses will then be relative to the assumed amplitude. Therefore, mass one will be assumed to have an amplitude of unity for each mode.

Using the values of $Q^n{}_r$ given in Table A, the values of $x^n{}_r$ are calculated and tabulated in Table B.

TABLE B

Table of values for $x^n{}_r$

$\downarrow n$ \ $\rightarrow r$	1	2	3	4	5
I	1	−403.95	+662.62	−596.07	+236.96
II	1	−263.48	+111.20	+231.10	−178.51
III	1	−109.36	− 98.68	+ 6.37	+105.33
IV	1	− 12.52	− 22.76	− 30.34	− 34.37

A very useful check for these computations is possible by numbering the masses and springs in figure 2 from right to left from which can be written

$$x^n{}_2 = (1 + \frac{I_1}{k_1} u^n)\, x^n{}_1 \qquad (11)$$

Rearranging equation (11), we have

$$x^n{}_1 = \frac{x^n{}_2}{1 + \frac{I_1}{k_1} u^n} \qquad (12)$$

From Table B, using the values of $x^n{}_4$ which will be $x^n{}_2$ for equation (12), $x^n{}_1$ can be calculated which should be equal to $x^n{}_5$ of Table B. This comparison is tabulated in Table C.

TABLE C

$\downarrow n$ \ $\rightarrow r$	5 r from left to right	1 r from right to left
I	+236.96	+237.52
II	−178.51	−178.84
III	+105.33	+146.37
IV	− 34.37	− 34.37

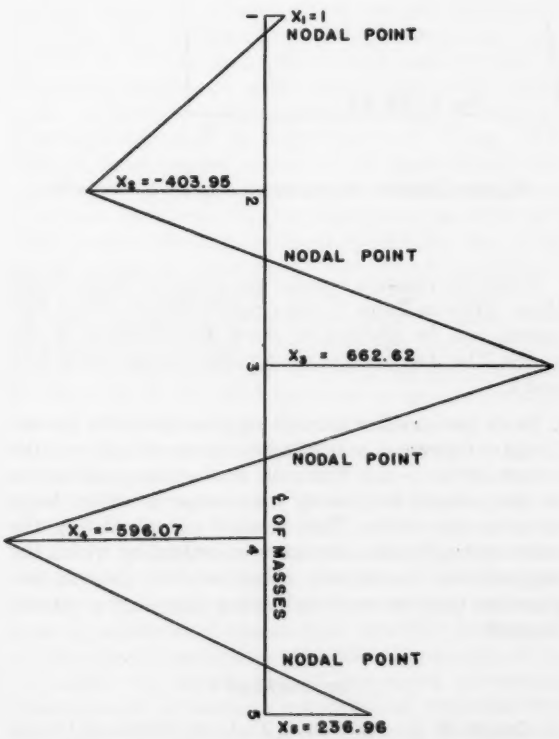


Figure 3. Relative displacement diagram for Mode I.

It will be noted that these values of x check with the exception of mode III. The natural frequency of mode III was given in reference (1) as $u = -14.347\ (10^6)$ rad/sec^2. In order to get identical numerical values by the check equation, it was necessary to change the frequency of mode III in reference (1) to $u = -14.254\ (10^6)$ rad/sec^2. This new value of u when checked in the frequency equation given by reference (1) made the frequency equation equal to zero.

A Table D will now be constructed for new values of $Q_r{}^{III}$

TABLE D

Corrected values of $Q_r{}^{III}$

$\downarrow n$ \ $\rightarrow r$	1	2	3	4
III	−108.64604	+0.91640	+1.04973	+1.04973

A Table E will now be constructed for new values of $x_r{}^{III}$ using the values of $Q_r{}^{III}$ from Table D.

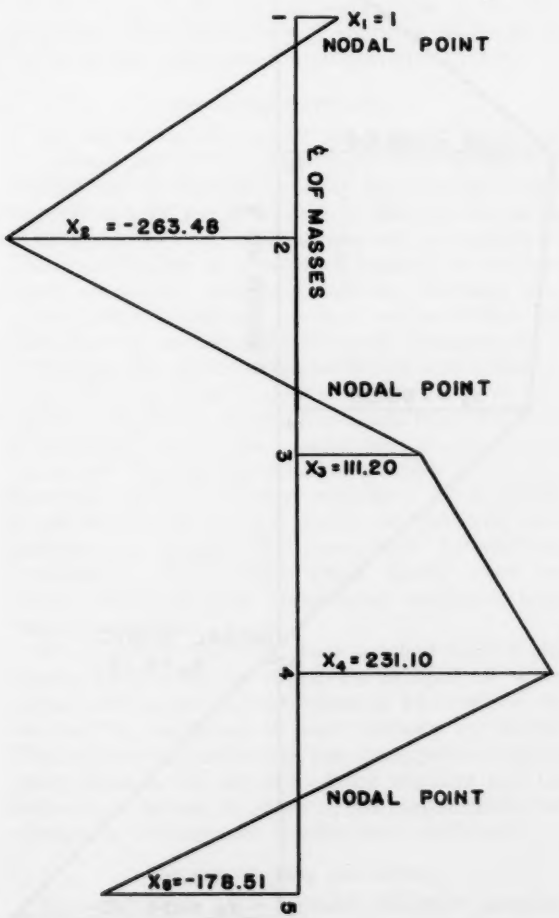


Figure 4. Relative displacement diagram for Mode II.

TABLE E

Corrected values of x_r^{III}

↓n \ →r	1	2	3	4	5
III	1	−108.64	−98.56	+5.18	+104.00

A check can now be made by the use of equation (12).

This comparison is shown in Table F.

TABLE F

↓n \ →r	5 r from left to right	1 r from right to left
III	+104.00	+104.18

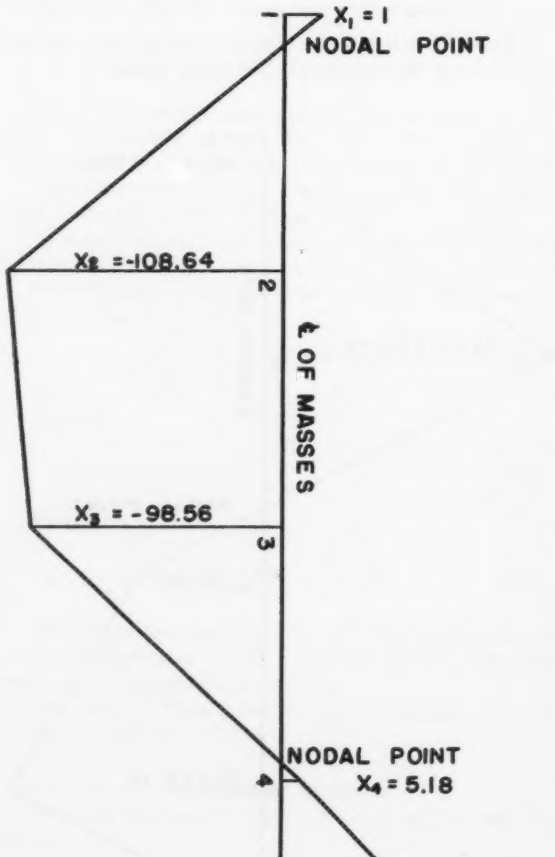


Figure 5. Relative displacement diagram for Mode III.

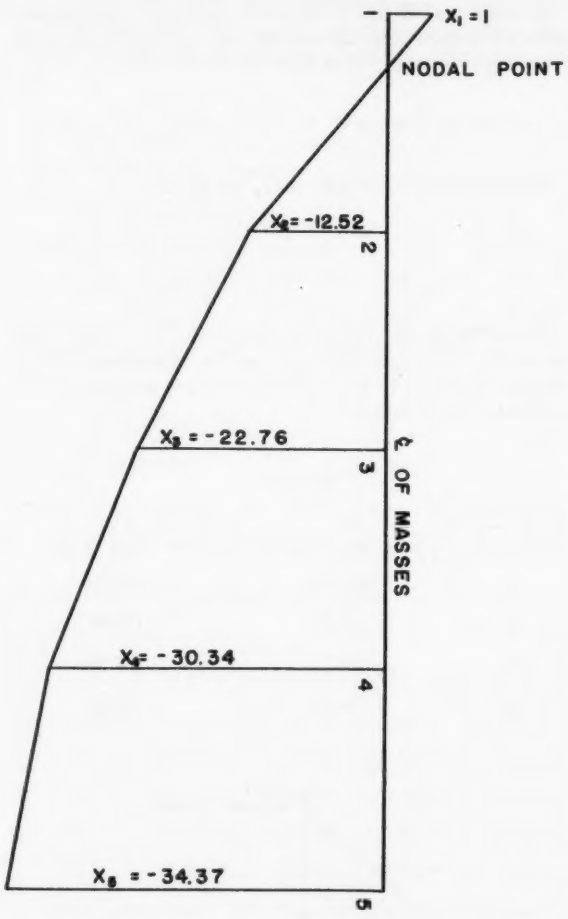


Figure 6. Relative displacement diagram for Mode IV.

From the relative amplitudes given in Table B and those given in Table E, the relative displacement diagrams can be plotted to show the location of the nodes. The displacement diagrams are figures 3, 4, 5, and 6.

Since the stresses introduced into the shafts by torsional vibrations are directly proportional to the values of $(x_{r-1}-x_r)$ it is seen that a very small error in the natural frequency may cause a rather large error in the stress. This method of calculating the relative amplitudes furnishes a method by which the approximate numerical values of the natural frequencies may be corrected to any degree of accuracy desired.

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PROFESSIONAL STANDARDS AND EMPLOYMENT CONDITIONS

ACKNOWLEDGEMENT

This is a slightly condensed version of a report of the Engineers Joint Council, as published in the June, 1956, issue of "Mechanical Engineering."

INTRODUCTION

UNLIKE THE MEMBERS of most learned professions, the engineer usually is an employee rather than a private practitioner. Surveys indicate that about 80 per cent of professional engineers are in the employee classification, and this situation sometimes creates special problems which are not inherent in the other professions. One such problem is how specifically to create and maintain an employment atmosphere consistent with high professional standards. Certain conditions of employment have had a profound influence on engineers and, among other factors, have caused a number of professional employee groups to turn to collective bargaining. There is a need, therefore, for the engineering profession to state clearly the employment conditions that engineers expect as professional men. Employers should align their policies with respect to the engagement of professional-engineering personnel to meet these expectations. Mutual understanding between employers of engineers and the engineering profession is essential to the establishment of an environment which will encourage the individual engineer to achieve full professional stature. A special committee of Engineers Joint Council was charged with a study of this employment problem and the preparation for Engineers Joint Council of "a means of education of and vertical communication to the membership of the constituent societies (including students) concerning conditions surrounding unionization of professional personnel." Another assignment of the special committee was the preparation of information for employers of engineers concerning employment practices, educational opportunities, and general measures for professional development that influence the attitudes of engineers toward a true professional outlook. This study treats but one of the many problems confronting the profession. Engineers Joint Council will continue its study of the problems related to the employed engineer.

THE PRESENT SITUATION

The expansion of engineering from its beginning in military and civil engineering a century ago to a multiplicity of disciplines today has created a host of problems. Of major concern to the engineer is his relationship as a professional man with his employer. This relationship is influenced largely by employment conditions including salaries, training programs, security policies, levels of responsibility, job classification, and identification with management.

Because the needs, responsibilities, and contributions of professional employees have not been recognized adequately, in some instances there has been a movement toward the unionization of engineering personnel. This has had an adverse effect on the professional concepts of many engineers, for a professional man must rely first on his own personal competence and integrity for recognition. In addition, confidential relationships which should exist between employers and professional engineers have been jeopardized.

The fact that there has been a trend toward collective bargaining by engineers, in spite of widespread reluctance to participate in such action, indicates the existence of unsatisfactory conditions. The engineering profession and management have a great stake in the solution of the problem and the latter must accept its share of the responsibility for alleviating unfavorable employment conditions.

CAUSES OF THIS CONDITION

Reasons which have fostered collective bargaining among engineers have been studied and may be grouped as follows:

Professional Treatment

(a) A feeling among engineers that they were not identified with management, whether they were employees in industry, private engineering firms, or public service.
(b) Inadequate channels of communication between top management and nonsupervisory engineers.
(c) Inadequate recognition of the engineer as a professional employee.
(d) Assignment of engineers to subprofessional work.
(e) Undue retention of engineers in specialized and narrowly compartmentalized assignments.
(f) Lack of appropriate means for resolving individual problems.

Personal Treatment

(a) Inadequate recognition and treatment of the engineer as an individual.
(b) Lack of broad position classifications and appropriate titles by which the engineer could measure his progress.
(c) Inadequate or nonexistent plans for training and job rotation.
(d) Inadequate understanding of promotional policies and belief that progress and promotions were not commensurate with ability and performance.
(e) Feeling of insecurity of employment.
(f) Management's human relations knowledge and skills have not kept pace with the expanded utilization of engineers.

Financial Treatment

(a) Engineering salaries not commensurate with fundamental contribution.
(b) Too small a differential between the pay of engineers and members of the skilled trades.
(c) Salaries of experienced engineers not sufficiently increased, in comparison with present starting salaries.
(d) Wide variation in salaries paid to engineers doing comparable work in different organizations.
(e) Dissatisfaction with merit review systems and inadequate understanding of salary administration.

Faced with these conditions, some engineers have resorted to unionization in the belief that corrective action could be effected only by pressures on management through collective bargaining. Even though they may have realized that professionalism requires freedom of action, these engineers appear to have been willing to submerge this principle in their attempt to get more pay and better working conditions through union activity.

SUMMARY OF HISTORICAL BACKGROUND

The accelerated development of mass-production techniques in this century stimulated a rapid rise in labor-union activities. Labor and management faced common problems of increasing complexity. In 1935 the United States Congress enacted the National Labor Relations Act, better known as the Wagner Act, which guaranteed to employees the right to organize and to bargain collectively and protected labor unions against specified unfair labor practices on the part of management. At that time there was little realization on the part of the professions of the potential impact of the Wagner Act on professional employees. However, the established labor unions soon took advantage of the situation and it was not long until many professional employees found themselves included, against their individual desires, in heterogeneous bargaining groups.

Some engineering societies, particularly the American Society of Civil Engineers, undertook to chart a course of action designed to assist professional employees against inclusion in heterogeneous groups. At first, the effort met with but minor success. Later, Engineers Joint Council determined to present its views to Congress with the hope that the Wagner Act might be amended to provide recognition of the status of professional employees and to enable them to act effectively on their own behalf. Pertinent clauses were included in the Labor Management Act enacted by the Congress in 1947—better known as the Taft-Hartley Act.

Of interest to the engineering profession, this law specifically provides under Section 9 (b):

> The Board shall decide in each case whether, in order to assure to employees the fullest freedom in exercising the rights guaranteed by this Act, the unit appropriate for the purposes of collective bargaining shall be the employer unit, craft unit, plant unit, or subdivision thereof; PROVIDED that the Board shall not (1) decide that any unit is appropriate for such purposes if such unit includes both professional employees and employees who are not professional employees unless a majority of such professional employees vote for inclusion in such unit...

The term *professional employee* as included in the Act reads

> (a) Any employee engaged in work (i) predominantly intellectual and varied in character as opposed to routine mental, manual, mechanical, or physical work; (ii) involving the consistent exercise of discretion and judgment in its performance; (iii) of such a character that the output produced or the result accomplished cannot be standardized in relation to a given period of time; (iv) requiring knowledge of an advanced type in a field of science or learning customarily acquired by a prolonged course of specialized intellectual instruction and study in an institution of higher learning or a hospital, as distinguished from a general academic education or from an apprenticeship or from training in the performance of routine mental, manual, or physical processes; or, (b) any employee who has (i) completed the courses of specialized intellectual instruction and study described in clause (iv) of paragraph (a), and (ii) is performing related work under the supervision of a professional person to qualify himself to become a professional employee as defined in paragraph (a).

Under the Taft-Hartley Act a group of professional employees in any place of employment may decide by majority vote of their own numbers whether they want to form a unit of their own for collective-bargaining purposes, to join with some other bargaining group, or to refrain from collective bargaining entirely.

It was hoped that the amended act would provide a satisfactory solution to the inclusion of engineers in heterogeneous unions. Professional employees could dissociate themselves from heterogeneous groups. It was not expected that employees of professional status ever would desire anything like a nation-wide bargaining union. It was hoped that labor unions

would respect the statutory rights of professional employees.

Those hopes today lack much of full realization.

A number of bargaining groups of professional employees have come into existence. Some appear to have functioned constructively; the same hardly can be said of others. Already there is a nation-wide union, self-designated as an engineering union, which aspires to power. Although some professional employees have been able to disassociate themselves from heterogeneous groups, craft unions, particularly in the construction industry, are forcing more and more engineers into their ranks by bringing economic pressure upon employees, thus avoiding the election machinery of the Taft-Hartley Act. Clearly, many members of the engineering profession and employers of engineers are not doing enough to insure enforcement of the letter and spirit of the law.

The recent merging of the American Federation of Labor (AFL) and the Congress of Industrial Organization (CIO) brings into being a large and powerful labor organization among whose objectives are increased efforts toward unionization of office employees and technical personnel. That effort will have direct impact on professional engineers.

To obtain reliable statistics regarding the current status and thinking of a cross section of the engineering profession, four constituent members of EJC, namely, ASCE, ASME, AIEE, and SNAME, polled 117,917 of their members on specific questions concerning collective bargaining. Of those polled, 66,938 or 57 per cent responded.

Returns showed that 48,082, or 72 per cent, of the 66,938 respondents opposed collective bargaining for professional engineers, and that 44,168, or 66 per cent, felt that collective bargaining is incompatible with professional status.

Further, the 66,938 responses showed that less than 4 per cent were actually members of established collective-bargaining groups; 27 per cent reported as not being opposed to collective bargaining; 20 per cent reported that they believed collective bargaining would be advantageous to them; and finally, less than 1 per cent of the membership of three member societies (the fourth did not ask the question), would prefer to be represented by a craft labor union.

These results present a challenge to the engineering profession and to engineering management. The thinking of the remaining 43 per cent of the 117,917 members polled, who did not respond to the questionnaire, is still unknown, but, assuming that the sample was representative, there would then be 30,300 members not opposed to collective bargaining for professional engineers.

These results emphasize the situation confronting the profession in spite of the protective clauses in the Taft-Hartley Act.

STATEMENT OF THE PROBLEM AND SUGGESTED SOLUTIONS

A summary of the foregoing might lead to two basic reasons for the present situation:

1. Engineers have not always realized and understood the professional characteristics of their roles.
2. Management has not always realized and accepted its obligations to engineers.

If these are the causes, the problem then may be stated as how to get the engineer to appreciate the professional characteristics of his position and how to get management to realize and accept its obligations to its engineers.

Immediately certain solutions present themselves, and these may be listed under five main headings:

1. Point out to the engineer and re-emphasize to him that engineering is a profession and that he therefore has certain definite responsibilities.
2. Point out to management, through all feasible ways, that it has responsibilities to the engineering profession.
3. Point out to professional societies the part which they should play in the advancement of their profession.
4. Point out to engineering educators their responsibilities for developing professional concepts in their students.
5. Point out to society the contribution of the engineer to its general welfare.

ENGINEERING—A PROFESSION

Engineering is the art and science by which the properties of matter and energy are made useful to man in structures, machines, and products. Accomplishment of these ends requires not only scientific training, but also creative imagination, judgment, and an appreciation of the economics involved. The work of the engineer is predominantly intellectual and varied. The dictionary defines engineering as a mental activity rather than a manual skill. The engineer must exercise discretion and judgment, he must wish to serve, and his relationship with management must be one of confidence; in fact he is part of management.

The engineer's code of ethics requires that "he will have due regard for the safety of life and health of the public and employees who may be affected by the work for which he is responsible" and that "he will act in professional matters for each client or employer as a faithful agent or trustee."

Since clients and employers usually do not have the technical knowledge necessary to judge technical work, the engineer is bound to place their protection above his personal convenience or his immediate personal gain.

The work of a truly professional engineer is so far from a routine established pattern that only he can provide the initiative, the discretion, and judgment to achieve the successful accomplishment of his particular tasks. Because he alone knows with what comprehension, ability, and likelihood of success he approaches his assignment, the professional must accept individual responsibility or else advise his client or employer that other help is needed.

Professional attitude involves the following five basic concepts:

1. A social consciousness, a desire to contribute *to* rather that simply to benefit *from* civilization; a resolve to place the public welfare above other considerations.
2. The acquisition of special skills on a high intellectual plane, generally evaluated by means of self-imposed standards of excellence.
3. A sense of trusteeship—personal responsibility to protect the client's or employer's interest.
4. Individual initiative and acceptance of individual responsibility, both of the highest order.
5. A right to expect and to receive adequate financial recognition.

Prestige, however, is something that must be won. It cannot be bought or automatically accorded through affiliation with an organization. It is something that one can *command* but never *demand*. In the final analysis, an engineer achieves professional standing only to the extent that he accepts his responsibility to himself, to his client or employer, and to society.

Attainment of a degree in engineering from an institution of recognized standing implies that the graduate has mastered a certain curriculum and that he has the ability to understand, to assimilate, and to apply the knowledge that qualifies him to become a member of the engineering profession.

EMPLOYEE'S RESPONSIBILITY

"As an engineer, I will participate in none but honest enterprise. To him that has engaged my services, as employer or client, I will give the utmost of performance and fidelity." *(Faith of the Engineer.)*

The engineering employee is bound by the same ethical and moral principles that apply to a member of any other learned profession. The responsibilities of an engineering employee are many. He is obliged to perform the professional assignments entrusted to him to the best of his knowledge and ability. He should give needed professional counsel in his special field and render loyal service. He should respect the economic problems of his employer. He should be thorough, expeditious, original, and accurate in the execution of his duties and assignments. He should have a rational attitude toward his work and fulfill each task with a minimum of supervision. At all times he should strive to improve the quality and increase the quantity of his output.

Education is important to the engineer and he should foster its continuance for those who are subordinate to him. He should strive to recognize and to utilize the diverse capacities of all fellow employees. He should strive for good planning and clear concise reports. He should be friendly and maintain a good appearance. He should develop the ability to be a good listener as well as to express his thoughts effectively.

Any employee who is unwilling to assume responsibilities beyond those accompanying his present job has little right to be critical about lack of advancement. If he feels that he is not getting earned recognition, it well may be that critical self-appraisal is in order. One cannot just wish himself up the ladder or depend on someone else to push or pull him along the way to success. The fact that a man has acquired a bachelor's degree in engineering does not, of itself, entitle him to any lasting professional recognition. It remains for each individual to prove by his own ability, integrity, and conscientious application to duty that he deserves recognition.

MANAGEMENT'S RESPONSIBILITIES

Surveys show that more than 40 per cent of management were trained as engineers. It seems illogical, therefore, that often there is inadequate communication between management and engineers with consequent lack of understanding on the part of management of the reasons for dissatisfaction among professional employees.

Management must recognize the inherent professional character of engineering work. It should be a policy of management to use its professional employees to the maximum of their capabilities. Except during the training period the engineer should not be assigned to tasks which do not require his technical training and he should be accorded individual and professional status commensurate with the quality of his contribution.

There must be opportunity for a continuation of education. It is important that professional employees be given opportunities to participate in activities of scientific and technical societies. It is important that they receive credit for their contributions to the advancement of technical knowledge or the profession as a whole.

There must be adequate communication between management and the professional employee. There should be organized orientation and training programs for new employees. Engineers need to understand the basic policies of their employer. They need to know their responsibilities and their opportunities for advancement. Adequate management-employee communications require a day-to-day relationship supplemented by periodic performance reviews, and other appropriate techniques.

Salaries must be established which will recognize the contribution of the professional employees as related to that of other groups. Salary differentials between various levels of technical experience have been substantially narrowed during recent years. Engineers who, after a period of satisfactory employment find their salaries are only slightly higher than those of the recent graduate and possibly lower than those of a skilled craftsman are not working in a favorable atmosphere.

Management must minimize the fear of job insecurity by adopting feasible means for stabilizing the employment of professional personnel and suitable termination policies. Since many engineers become managers, there is a need to insure that they are em-

ployed and developed in an atmosphere which will fit them for their future responsibilities. Executive talents must be developed by experience and training in those phases which lead to managerial responsibilities.

Engineering Societies' Responsibilities

The engineering societies must take the lead in the advancement of the profession. Among the basic responsibilities of the engineering societies are the establishment of standards of ethical conduct, rigid requirements for admission to membership, accreditation of educational institutions which grant engineering degrees, and awards and prizes in recognition of worthy contributions to the advancement of the profession.

Current efforts of national committees to encourage professional development of engineering-society members and to promote recognition by the public of the professional character of the engineers' work should be expanded. An objective evaluation of the problem should be continued, followed by specific recommendations for the good of the profession. Engineering societies should adopt official statements for membership information with respect to collective bargaining to the extent permitted by their charters and constitutions. They should acquaint their memberships with those provisions of the Taft-Hartley Act which have a special significance to professional engineers. Constructive programs for encouraging professional consciousness on the part of engineers both before and after graduation should be sponsored. Therefore, the engineering societies and Engineers Joint Council should inform managment as to the standards that will contribute to full professional achievement.

The engineering societies should provide guidance and assistance to educational institutions confronted with any problem which is detrimental to the achievement of full professional training of students.

Engineering Education's Responsibility

Engineering colleges have a primary responsibility for developing professional concepts in engineering students. Professional concepts should be developed through their application to the solution of engineering problems, in the technical courses, lectures, association with students, and by good example.

Opportunities for engineering educators to become better acquainted with the total environment in which engineers work should be expanded through temporary employment in nonacademic fields and the utilization of employers with "professional vision" in the classrooms and student seminars. Such activities enable students to appraise their status more realistically upon graduation.

Conclusions and Recommendations

There are obligations and responsibilities resting on both employer and employee. Each, of course, has responsibility to advance his own welfare. Beyond that, and yet a part of it, each has responsibility to the other and to society. Grave responsibilities for inculcating and developing professional consciousness in young members of the profession rest upon the educational institutions and professional societies. Various phases of such responsibilities have been stressed in the several sections of this report.

Without a sound technical foundation no man can become a competent engineer. But more than technical competence is demanded of one who expects to be recognized as a professional person. One must understand and observe appropriate ethical standards and it is important to cultivate proper understanding of such standards.

The ECPD program "The First Five Years of Professional Development" is an excellent step in the right direction. Here is opportunity for the engineering societies, the colleges, industrial management, and civic institutions to work together to aid young graduates in continuing their education and in adjusting themselves to conditions to be met in the practice of their profession.

The present report has been prepared with full realization that the subject refers chiefly to one phase of professional life. An attempt has been made to identify factors that have significant bearing on the specific problem under consideration. Concerted efforts by all concerned with advancement of the profession are required if satisfactory solution is to be found. It is believed that if the recommendations submitted are followed by those to whom they are directed, substantial improvement in the standing of the profession will result.

CYLINDER LINER WEAR

ACKNOWLEDGEMENT

Börje Olsson, of the Engineering Department, A/B Götaverken, Gothenburg, Sweden, is the author of this article. It was published in the June, 1956, edition of "The British Motor Ship."

It is well known that fuel suppliers no longer furnish complete analyses of their fuel oils, as was frequently the case before the war. Chief engineers today must generally content themselves with data concerning the specific gravity, viscosity and flash point and in exceptional cases sulphur, ash, water and sediment.

About 200 samples of fuel oil from various bunkering places have been analyzed to gain an idea of the Diesel fuel oils available and a summary of the maximum values obtained from these is given below:—

	Max.	Min.
Spec. gravity 15°C	0.918	0.842
Viscosity °E/20°C	5.10	1.22
Carbon residue, Conradson, %	3.59	0.01
Ash %	0.036	0.001
Sulphur %	1.78	0.13
Vanadium mg./kg.	90	0
Cetane number	54.2	35.5

The limit values stated here must not be considered as extreme since analyses from other sources have been obtained which in some cases differ from those in the table, but they give an idea of the present limits. Clearly, the variations are very large, and special note should be taken of the differences in viscosity, sulphur content and carbon residue values.

By grouping the analyses from the same bunkering areas, an attempt has, however, been made to bring out the characteristic properties of the fuel oils concerned. In so doing the distillation curves of the samples have been a good aid. By comparing them we have been able to deal with the same fuel oils although the samples were often taken from different ships. This procedure has made it possible to obtain some characteristic fuel oils of some ordinary bunkering places.

Thus Fig. 1 shows the average figures for the sulphur and carbon residue contents. The pair of bars farthest to the right, however, represents only one sample which is quoted here as an example of the high sulphur and carbon residue contents which

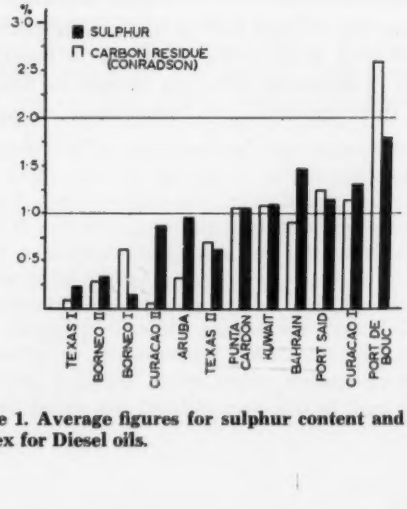

Figure 1. Average figures for sulphur content and Conradson index for Diesel oils.

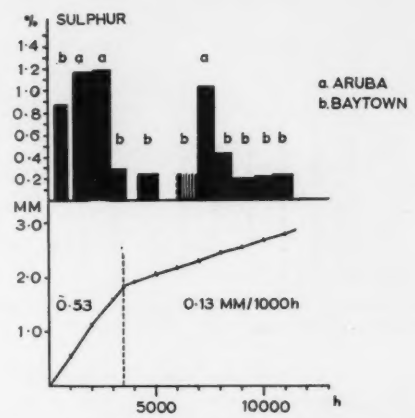

Figure 2. Cylinder wear related to sulphur content in the fuel.

may occur in Diesel oils. The figure shows that the "purest" oils in this regard were found in Texas and in Borneo. Furthermore, by analyses and distillation curves different brands of oil from the same places have been separated. (Texas, Borneo and Curaçao).

The percentage values for sulphur and carbon residue are approximately of the same magnitude except in a few instances; Borneo I, Curaçao II and Aruba. In the first case a low sulphur content is combined with a high carbon residue value but in the last two, the proportions are reversed. It may be noted that the first three oils in the figure have specific gravities of about 0.90, and viscosities ranging from 2.5 to 4.0 (°E/20° C), i.e., they are heavier and more viscous than the others which have specific gravities of 0.85 to 0.88, and viscosities of 1.5 to 2.0.

When it is desired to follow the influence of a certain fuel oil upon cylinder wear, great difficulties are encountered. There are very seldom straightforward cases where an engine uses the same fuel for a long period. Generally the ships bunker every other month whereas the pistons are inspected at the most twice a year, which implies that several different fuel oils are used for a cylinder during a piston running period.

Information has, however, been obtained of some characteristic cases showing the influence of the fuel oil on wear. Fig. 2 shows the average wear for a six-cylinder engine in a tanker and the sulphur content of the fuel oil so far as it has been possible to get the analyses which were made from bunkering and from fuel oil samples at our own laboratory. The gaps in the diagram refer to bunkers from (left to right) Gothenburg, Stockholm, Gothenburg and Porto la Cruz, the sulphur contents of which it has, however, not been possible to ascertain; but the data on specific gravity, viscosity and flash point tally with those of the preceding bunkers at the same place, and for this reason it is likely to be the same oil. The width of the bars indicates generally how long the ship has operated on one class of fuel oil.

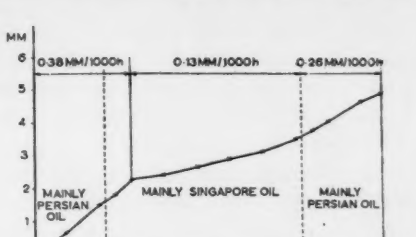

Figure 3. Cylinder wear with different fuels.

The average wear during the first 3,500 operating hours was 0.53 mm./1,000 hr., while the sulphur content of the fuel oil at the same time was somewhat over 1%. Then the wear diminished to 0.13 mm. while the sulphur content of the fuel oil fell to the order of 0.2 to 0.3% for most bunkerings. Cylinder wear is frequently somewhat higher during running-in than when steady conditions are reached, but there can never be any question of such a noticeable transition. In this case it can thus be asserted with good reason that the cylinder wear has been directly proportional to the sulphur content of the fuel oil.

Fig. 3 shows the average wear of a nine-cylinder engine in a tanker. Information was available as to where the tanker had bunkered but not the analyses. During the first year the ship bunkered mainly in the Persian Gulf, in the following two years in Singapore (Borneo oil), and finally, during the fourth year, it was moved again to the Persian Gulf. The wear curve shows in its first part a transition equally as noticeable as in the preceding example: the final part indicates an increase in wear when returning to the original type of fuel oil. Grouping of fuel oil types from different bunkering ports has shown that Borneo oils, when compared with those from the Persian Gulf, have considerably lower sulphur and carbon residue content and, as pointed out, a higher viscosity.

Recently there was an opportunity for measuring the cylinder wear in two Argentine tankers built in Sweden, which had been running without interruption for 10 years. The cylinder wear of these two ships after running times of 50,000 and 45,000 hr. respectively, averaged 0.05 and 0.06 mm/1,000 hr. The fuel oils used were mostly of Argentine origin and were, in addition, made up in part by Russian oils from Odessa and can be classified as gas oils. The oils analyzed show viscosities ranging from 1.43 to 1.50 °E/20° C. (40 secs. Red. No. 1), a carbon residue content of some hundredths of 1% and sulphur ranging from 0.20 to 0.60%. According to analyses obtained some five years ago the sulphur content has been as low as 0.04%.

The wearing faces of the cylinder liners in these ships were very dark, which means that they had been allowed to oxidize to a high degree. In this case it could hardly be a question of metallic contact between ring and liner. (Bright liners, like bright plain bearings which have been operating a long time, show that the oil film has not been intact.)

Statistics show that, generally, wear rates still have a tendency to rise. Thus, for instance, the wear in tankers has risen from an average of 0.36 mm/1,000 hr. for 1946–1952, to 0.46 mm. for 1952–1953. The figures in each case refer to average values for 36 tankers. All examples mentioned hitherto have had—so far as it has been possible to check—cylinder liners of unalloyed pig iron and ordinary piston rings which have been manufactured also of pig iron.

CONCLUSIONS FROM THE INVESTIGATION

From what has been stated above, the following conclusions can be drawn:—

(1) Except for purely operating conditions the quality of the fuel oil determines the extent of of the cylinder wear.

(2) The quality of the fuel oils available at present varies within very wide limits, the inferior quality being by far in the majority.

(3) Unalloyed pig iron no longer meets the demand for acceptable cylinder liner material in conjunction with the Diesel oils available at present.

(4) The more general transition to heavy oil operation underlines the demand for special steps to reduce cylinder wear.

In order to reduce cylinder wear the following ways appear to be open:—

(1) More wear-resistant cylinder liner material.

(2) Chromium-plated cylinder liners.

(3) Chromium-plated piston rings.

(4) More efficient lubricants and lubrication.

CYLINDER LINER MATERIAL

For many years, unalloyed pig iron has successfully been used as cylinder liner material. The fine laminar pearlite structure with sufficient size and uniform distribution of the graphite has shown the best wearing characteristics. As indicated above, this material can still be used with success together with a few fuel oils. It was, therefore, important to find an alloy pig iron material of far greater wear resistance with a manufacturing cost which, at the same time, was within reasonable limits.

The alloys tested contained as main alloy components: nickel, copper, chromium and vanadium. Furthermore, tests have been made with modifications concerning the phosphorus content. Thus, cylinder liners of more than about 10 different alloys have been made and tested in full scale under actual service conditions, i.e., they have been operated along with unalloyed pig iron liners in the same engine on board ship. In addition, cylinder liners of other makes have been subjected to similar tests. To ensure reliable results in each case, at least two cylinders of the engine have been equipped with the test liners concerned. In several cases half the cylinder liners were test liners.

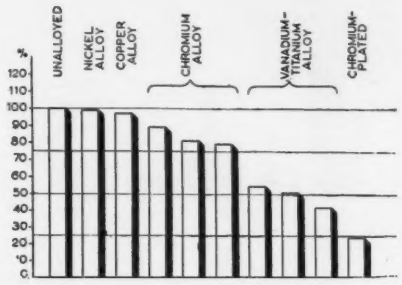

Figure 4. Wear rates of different materials compared with that of unalloyed cast iron.

Results of the various tests have been grouped as shown in Fig. 4. The height of the bars gives the average figure for the wear relationships for the various tests in relation to unalloyed pig iron and, reckoned from the left, represent: nickel alloy, copper alloy, three chromium alloy liners with differing phosphorus contents, three vanadium-titanium alloy liners—also with differing phosphorus contents—and chromium-plated liners so long as the chromium layer was intact. These results show that pig iron material with nickel or copper as the main alloy element has caused a hardly noticeable reduction in the cylinder wear rate whereas the chromium alloys produced a reduction of about 20% and the vanadium-titanium alloys some 50%.

As to the importance of the phosphorus content, contradictory results were obtained. Thus, for instance, with chromium alloys the material with a low phosphorus content had a higher wear than that with a high phosphorus content while the relation was inverse with the vanadium-titanium alloys. (Phosphorus contents in the chromium group from

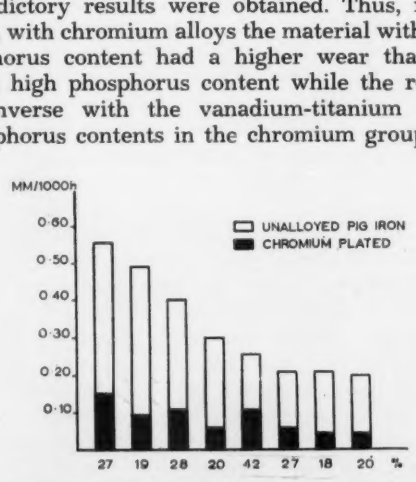

Figure 5. Wear rates encountered with chromium-plated liners and unalloyed cast iron liners in the same engine.

the left: 0.15, 0.60, 0.90%, and in the vanadium-titanium group 0.60, 0.20, 0.10%.) However, the result must be accepted with some reservation, since the tests in each case were based on only one ship.

On the other hand, the vanadium-titanium alloy material, vantit, with 0.20% of phosphorus has been tested in more than 10 engines in different ships and the wear rate of cylinder liners of this material is undoubtedly only half that of unalloyed pig iron liners.

CHROMIUM-PLATED CYLINDER LINERS

Performance results have been gathered on some 60 chrome-plated liners from 15 different ships. In the early development of chromium-plated cylinder liners it sometimes happened that the chromium peeled off from large areas, causing trouble in the cylinder, but modern methods have now eliminated these difficulties. In some cases, however, wear has been "abnormally heavy," so far as chromium is concerned, but this applies only to a few instances.

The wear results obtained in comparative tests with chromium-plated and non-chromium-plated pig iron liners in the same engine show very good agreement inasmuch as the relationship of the wear between these two types of liners has been fairly constant, though wide divergencies have occurred in the absolute values of wear in the various engines. The average wear for chromium-plated liners in relation to non-chromium-plated pig iron liners has proved to be 23% and ranged from 18% to 27% in the various tests. As mentioned above, exceptions have occurred and in this connection the wear relationship has been as much as 42% in one test. The comparison refers to wear relationships before the chromium layer of the liners was worn through and in all cases the liner material consisted of unalloyed pig iron. (The figures must, therefore, be doubled for vanadium-titanium alloy liners as is shown by the comparison of different pig iron materials.)

Fig. 5 shows the results from the tests in the various vessels. As is evident, the wear of the non-chromium-plated liners varied from 0.56 to 0.20 mm./1.000 hr. while the variation in the wear of the chromium-plated liners was 0.15 to 0.04 mm./1,000 hr. The percentage relationship in the various tests is given under the appropriate bar. The one exception is shown.

Since the relationship between the wear of chromium-plated and non-chromium-plated liners is almost constant and independent of the absolute extent of the wear this conclusion is drawn: *The wear in chromium-plated liners is directly dependent on the quality of the fuel oil* as was the case with non-chromium-plated liners.

Chromium-plated cylinder liners generally have a chromium layer of about 0.40 mm. Theoretically, the chromium thickness can be made many times greater but in actual practice chromium-plating must in such cases be carried out in stages with honing as an intermediary step. Unless this is done, the current follows the least resistance and consequently accelerates the peeling-off of chromium. Therefore, the price for liners with a thick layer of chromium becomes high, but according to information received, liners with a 2-mm. chromium layer have been made. These liners were for a double-acting two-stroke engine with liners made in one piece and very expensive to replace since their casting entailed great difficulties.

WEAR IN TANKERS AND DRY CARGO SHIPS

If an overall comparison of cylinder wear between tankers and dry cargo ships is made, statistics show that heavier wear is encountered with tankers. The wear-rate figures from a period covering 1946–1952 have shown for tankers 0.36 mm./1,000 hr. and for dry cargo ships 0.26 mm./1,000 hr. (unalloyed pig iron liners). The difference in wear between tankers and dry cargo ships is due mainly to the fact that most tankers bunker fuel oils in the Persian Gulf and Venezuela with a relatively high sulphur content; but it is due also to the more difficult operating conditions, i.e., long running time at sea and very limited time for inspection and maintenance.

A question of obvious importance is how wear develops after the chromium layer has been broken through. Experience shows that chromium-plated liners generally can be worn to the same diameter as non-chromium-plated liners, i.e., to approximately 1% of the original diameter without causing any difficulties.

The degree of wear after the chromium has been broken through is naturally determined by the composition of the basic material. It has been pointed out that as the rings bring up fine chromium dust from the remaining chromium layer at the bottom of the cylinder, the wear of the basic material should be less than that normally encountered. It has not been possible, however, to show the presence of chromium through spectographic examinations and it has thus been impossible to confirm this assertion.

Regarding the gain in service life won by chromium-plated liners in relation to those which are non-chromium-plated, it is likely to range from 50 to 100% depending on the basic material, provided that the liners are worn to the same diameter as non-chromium-plated liners.

CHROMIUM-PLATED PISTON RINGS

To obtain full-scale results of the value of chrome-plated piston rings a test was made with the largest type of Götaverken engine (760 mm. diameter, 1,500 mm. stroke), two pistons being fitted with chromium-plated piston rings. These rings were of steel and had a chromium layer ranging from 0.10 to 0.15 mm. The rings were fitted in the three top grooves, the other rings being of ordinary pig iron. In addition, the engine was equipped with chromium-plated liners on two cylinders, which offered a two-sided evaluation of the results in relation to both non-chromium-plated and chromium-plated liners. The

material of the cylinder liners was at that time unalloyed pig iron. The ship was delivered at the beginning of 1952.

After little more than six months had passed the first results from chromium-plated piston rings could be checked, and it was found the wear was half that of ordinary pig iron rings and twice that of chromium-plated liners. Consequently, a number of new tests were made, generally with good results. A fact noticed was that the wearing profile with chromium-plated rings was different from that of ordinary rings.

In a Diesel engine with longitudinal scavenging, the wear has a funnel-like profile with maximum wear directly in connection with the upper wearing edge, i.e., the T.D.C. position of the top piston ring. However, a wearing profile was obtained with chromium-plated piston rings in which the heaviest wear was encountered farther down the cylinder. It was generally about 150 mm. below the top wearing edge. In some cases the same wear has been noted at the wearing edge and 150 mm. below, but usually in this area is worn to a somewhat lesser degree.

This alteration of the wearing profile is likely to explain why cylinder wear is lower with chromium-plated piston rings. The oil film at the top of the cylinder liner is probably not intact because of burning, heavy ring pressure and low piston speed so that the wear is purely mechanical or is bordering on mechanical wear. With chromium-plated rings, owing to the bright face of the chromium, lower friction is obtained and consequently lower wear than with ordinary rings. Furthermore, no solid particles can fasten to the hard chromium on the wearing surfaces of the rings and exert a grinding action on the liner surface—the particles will glide off.

In continued tests chromium-plated piston rings have proved to have the same wear-reduction action in vantit liners as in unalloyed pig iron liners.

The chromium thickness generally ranges from 0.3 to 0.4 mm. The service life of this layer has proved to be 1,000 to 2,500 hr., which means that the rings must be replaced at every piston renovation to keep down wear. It would be desirable to have a still thicker layer of chromium since the period between piston overhauls in tankers generally exceeds 3,000 hr. According to some manufacturers of chromium-plated piston rings, a thicker chromium layer entails the danger of failure of the chromium due to the strains produced when the rings are forced over the piston top during fitting. However, according to information received, pistons have been made with a 1-mm. chromium layer but up to now it has not been possible to obtain the results.

SHOULD CHROMIUM-PLATED LINERS OR RINGS BE USED?

Regarding the choice of chromium-plated liners or rings this question is entirely one of economy. The factors of importance here are the operating conditions of the ship and the fuel oils to be used. In the dry cargo trade where there is frequently plenty of time for overhauling the engine and where a replacement of the cylinder liners does not cause any important interruption in operation, no special measures need be taken to keep down the costs produced by cylinder wear, particularly in cases where good fuel oil is available.

However, conditions in the tanker trade are different since a large proportion of the ships are time-chartered and each interruption not included in the contract immediately causes heavy extra cost to the shipping company. In addition, wear rates are, as already stated, generally higher due to the fuel oils available and the severe operating conditions. Therefore, cylinder wear must be held as low as possible so that the liners can be replaced at convenient periods, for instance, in connection with classification.

The highest-powered German motor trawler has been launched by H. C. Stülcken Sohn for Cranzer Fischdamper A. G. Named "Zephyros," she is 208 feet long, and will be driven by three six-cylinder Maybach Diesel engines having an output of 600 b.h.p. each at 1500 r.p.m.

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ENGINEERING ABSTRACTS

Number	*Abstract Title*
81-56	1956 Modern Plant Survey
82-56	Some Experiences in Vessels Equipped with Two-Stroke Cycle Harland and Wolff Opposed Piston Diesel Engines using Boiler Oil
83-56	Metallurgical Designing for Strength
84-56	Ultrasonic Welding
85-56	Tool Life Increased with New Steel
86-56	Packless Stuffing Boxes—Pro and Con
87-56	Surface Finish Inspection Methods
88-56	Power and the Future
89-56	Fire Resistant Hydraulic Fluids
90-56	Materials for Nuclear Power Reactors
91-56	How Additives Can Make Your Residual Fuels Burn Better, Cleaner
92-56	Engine Research
93-56	The Influence of Combustion on the Thermal Efficiency of Simple Gas-Turbine Cycles
94-56	Fire Fighting with Combustion Products
95-56	Nuclear Effects on Electronic Components
96-56	A Design Guide to Industrial Fasteners
97-56	Fin Stabilizers for Ships
98-56	Research at Pametrada
99-56	Lightweight Mech-Hydro Locomotive for Train X
100-56	The High Temperature Turbo-Jet Engine
101-56	Where Reactor Development Stands Today
102-56	25,000 Hours of Free Piston Engine Operation
103-56	High Temperature Brazing

Number *Abstract*

81-56 "1956 Modern Plant Survey"—B.G.A. Skrotzki; Power, V. 100, n. 9B, Mid Sept. 1956, pp. 35-62. Data are presented on steam, gas turbine and hydro plants beginning operations, under construction or in planning stages. Material includes: design survey of new steam central station installation; industrial institutional plants 250 psi and over; industrial and institutional plants less than 250 psi; stationary gas turbines in central station and industry; stationary gas turbines, small auxiliary and experimental; hydroelectric plants in the United States and Canada. Survey shows about 1,270 steam generators with total capacity 53.8 million lb. per hr. purchased in 1955 and early 1956. Some 63 steam turbines were installed with capacity of 815 mw. Largest boiler reported has capacity of 1,050,000 lb. per hr. Survey lists 413 gas turbines; 23 are Houdry and other process units and 390 are electrical and mechanical drive. These have a total nameplate rating of 1,855,000 kw. Largest gas turbine was a 40,000 kw planned by Swedish Power Board. Cycles for gas turbine include 349 open, 14 closed, 25 free piston, 2 semi-closed and 2 equi-pressure.

82-56 "Some Experiences in Vessels Equipped with Two-Stroke Cycle Harland and Wolff Opposed Piston Diesel Engines using Boiler Oil"—A. G. Arnold; Institute of Marine Engineers Transactions, V. LXVIII, n. 7, July 1956, pp. 201-245. Results of seventy-five voyages between the United Kingdom and The Far East made by nine vessels. Engines in all vessels had 750 mm bore with a combined stroke of 2,000 mm. Two cylinder liners were removed, after 13,000

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hours, due to cracking and not as a result of wear. Wear rates of liners are plotted for several vessels. Chrome hardened liners were tried but did not give results expected. Exhaust piston yoke on one engine was cracked and had to be replaced. Exhaust pistons, coating of piston crowns, piston rings, scavenge belts, scavenge belt fires, lubrication, cylinder oil, boiler oil, maintenance charges, supercharging and trials are discussed. A 350 KW gas turbine driven emergency generator set was installed in these vessels. Photographs, curves, tables, drawings, indicator diagrams and discussions of the paper are included.

83-56 "Metallurgical Designing for Strength"—C. Zener; Westinghouse Engineer, V. 16, n. 5, Sept. 1956, pp. 146-151. Design techniques are being developed to provide new metals and alloys to meet specific requirements. A new high-temperature alloy for steam turbines was recently developed using these techniques. Atomic structures and deformation are described. Design principles now available to the metallurgist are outlined. These new principles will result in the development of new materials at less cost and in shorter times.

84-56 "Ultrasonic Welding"—J. Byron Jones and James J. Powers, Jr.; The Welding Engineer, V. 36, n. 8, August 1956, pp. 761-766. Dissimilar metals can be bonded by introduction of ultrasonic energy into the metals at the areas to be in contact. Application of heat, aside from that generated by the vibratory motions, is not required. Strength and deformation of weld zones are shown. Discussion includes: basic problems in ultrasonic welding; welding systems; controllable welding variables; factors associated with mechanism of ultrasonic welding; present status of sheet-to-sheet welding. Feasible uses include: foil-thickness material bonding; foil thick materials bonded to heavy plate, rod or tube; welding of sintered aluminum powder products; welding of copper in gages up to 0.040 in.; hermetic sealing of small containers, squeeze tubes, impact extrusions. References.

85-56 "Tool Life Increased with New Steel"—J. Y. Riedel; Metal Progress, V. 70, n. 2, August 1956, pp. 69-71. A tool steel has been developed that has improved shock resistance and service life. This steel is improved for both hot and cold work applications. The nominal composition of this steel is 0.50% C, 0.70% Mn, 0.27% Si, 3.25% Cr, and 1.40% Mo. When fully annealed, machinibility is about 95% that of a 1% carbon steel. This steel, as a notching die, enabled production of 10,000 pieces where dies of other materials produced only 30 pieces.

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Punches made from this steel produced an average of 5,500 holes while other punches produced from 300 to 1,500 holes per punch. In hot riveting on boilers rivet sets ran to nearly 2,500 before recupping while standard rivet sets ran no more than 300 rivets.

86-56 "Packless Stuffing Boxes—Pro and Con"—Igor J. Karassik; Power Engineering, V. 60, n. 9, Sept. 1956, pp. 90-92. The weakest point of high speed boiler feed pumps is the packing. Present designs can now be made so that high pressure pumps can run from 60,000 to 120,000 hours between complete overhauls. However, packing requirements are to shut pumps down every 6 to 18 months for repacking. Mechanical seals and packless stuffing boxes are being investigated. They have both been tried. The packless stuffing box is the most promising at the present. In this unit a labyrinth breakdown bushing is substituted for conventional packing. Pumps operating in speed range from 6,000 to 9,000 rpm make the packless stuffing box more attractive than packing.

87-56 "Surface Finish Inspection Methods"—C. H. Good; The Tool Engineer, V. XXXVII, n. 2, August 1956, pp. 93-97. Methods and equipment for measuring and evaluating surface finish are presented. Instruments and methods include: reflectivity meter, air gaging, microscope, stylus techniques. Limitations of these are described. Various inspection techniques are summarized in tabular form. Illustrations, photographs and charts.

88-56 "Power and the Future"—T. W. F. Brown; North East Coast Institution of Engineers and Shipbuilders Transactions, V. 72, n. 8, July 1956, pp. 373-388. Power available and predicted for future is discussed. Sources include the earth and sun. Radiation is a direct use of sun while indirect uses include hydro-electric, wind and lightning. Tidal power, hydrocarbon fuels and nuclear power are reviewed. Efficiencies of various prime movers for converting heat energy to mechanical power are shown.

89-56 "Fire Resistant Hydraulic Fluids"—R. Q. Sharpe; Product Engineering, V. 27, n. 8, August 1956, pp. 162-166. More hydraulic systems for actuating machines are being designed to use fire resistant fluids. Many hydraulic and lubricating oils have a flash point of 375°F or greater and a fire point of 425°F. When lines fail under high pressure, oil can be atomized and readily result in a flash fire. Fire resistant fluids available include: water glycol mixtures; non-aqueous type such as tri-cresyl phosphate, chlorinated hydrocarbons, fluorinated hydrocarbons; water soluble oil emulsions. Properties of fire resistant fluids compared with petroleum oil. Tables and references.

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90-56 "Materials for Nuclear Power Reactors"—John M. Warde; Materials & Methods, V. 44, n. 2, August 1956, pp. 121-144. Material selection factors and materials for reactors are discussed. Data presented on structural materials including aluminum, stainless steel, nickel and nickel base alloys, zirconium, magnesium, molybdenum, titanium, graphite, silicon, carbide, cermets, plastics and elastomers. Shielding, controls, coolants, fuels, and fertile materials are reviewed. Properties of some materials are in tables. Illustrations and curves shown. Future outlook for power indicates that by 2,000 A.D. nuclear plants will be producing more power than all other sources combined at present time.

91-56 "How Additives Can Make Your Residual Fuels Burn Better, Cleaner"—R. S. Norris; Power, V. 100, n. 8, Aug. 1956, pp. 120-121. Residual fuels contain most of the compounds of sulfur, vanadium and sodium. These compounds are harmful to certain parts of boilers, gas turbines and diesel engines. Diesel cylinder liners and piston ring wear rates are as much as three times as high when burning residual fuel. Vanadium and sodium compounds are corrosive in a liquid state. Certain additives for residual fuels hold promise for use in diesels, gas turbines and boilers. These additives are known as BARSAD. They have been used in the following applications with residual fuels: 20 diesel ships for 18 months; a 650 psi, 825°F, 150,000 lb.-per-hr. boiler; and a C-2 cargo vessel.

92-56 "Engine Research"—Automobile Engineer; V. 46, n. 7, July 1956, pp. 254-263. Discussion of engine research including: diesel engine developments, high-speed sampling valves, fuel-line pressure measuring units, blowing rig, cold starting rig, traversing thermocouple, heat flow, residual fuel, injector temperature measurement and Alcock viscous flow air meter.

93-56 "The Influence of Combustion on the Thermal Efficiency of Simple Gas-Turbine Cycles"—L. S. Dzung; The Brown Boveri Review, V. 43, n. ¾, Mar/Apr. 1956, pp. 63-78. The entire problem of combustion, both internal and external to the medium circuit, is discussed. Thermodynamic principles, diabatic process without combustion, liquid fuel, dependence of basic process on medium, reaction parameters, and numerical examples are presented. Bibliography.

94-56 "Fire Fighting with Combustion Products"—The Marine Engineer and Naval Architect; V. 79, n. 958, August 1956, pp. 276-278. A fire fighting system consisting of an inert gas generator has been developed for extinguishing fires in cargo holds and machinery spaces. The unit as developed includes: horizontal combustion chamber, with water jacketed fire brick lining; an oil burner with fuel and air regulators; cooling chamber; water cooled diesel driving an air blower; generator for supplying power for accessory units. Diesel oil is used for fuel. The gas generator package is 9 ft. long, 4 ft. wide and 7 ft. high. Fuel consumption to meet requirements for a ship's hold of 115,000 cu. ft. is 25 gallons per hour. This system as installed on the motorship *Oti* costs about $21,000 and has been approved by Ministry of Transport.

95-56 "Nuclear Effects on Electronic Components"—Charles C. Robinson; Electrical Manufacturing, V. 58, n. 2, August 1956, pp. 96-99, 268, 270, 272. Important nuclear effects on electronic components are being investigated under a recently awarded Air Force contract. Wire insulation has reduced resistance proportional to radiation intensity. Gases may be liberated and rupture containers of oil filled and oil impregnated parts. Resistors change values from 5 to 15 per cent. Radiation, particularly gamma radiation, may cause phototubes to indicate false. Current tests under this program are designed to indicate changes in components during periods of irradiation. Results of this work will be prepared in a form suitable for use by the engineer in selecting an appropriate component for specific needs. References.

96-56 "A Design Guide to Industrial Fasteners"—Julius Soled; Machine Design, V. 28, n. 17, August 23, 1956, pp. 105-137. Seven basic categories of fasteners are presented: inserts, nuts, pins, retaining rings, rivets, screws, bolts, studs and washers. The items are illustrated, form, design features, materials, sizes, and applications are discussed. Standard and proprietary items are included.

97-56 "Fin Stabilizers for Ships"—M. D. Martin; Bureau of Ships Journal, V. 5, n. 5, Sept. 1956, pp. 15-21. A hydrofoil fin type stabilizer has been installed on the USS *Gyatt* (DDG-712). The installation cost approximately $380,000 and is the first for the U.S. Navy. The stabilizer is expected to have sufficient capacity to reduce rolling motions of the ship from 26° or more from the vertical to 1½° either side of the vertical. Main components of the power plant include electric motor, hydraulic pump and stroking servo system. Advantages of the stabilizer: aids in replenishing at sea; aids in navigation; improves crew efficiency, safety and comfort; aids in guided and ballistic missile handling and launching.

98-56 "Research at Pametrada"—The Oil Engine and Gas Turbine; V. XXIV, n. 276, August 1956, p. 164. High temperature development and design work is being done on gas turbines operating at 1200° C. The test turbine is a single stage machine. Temperature distribution tests on the combustion chamber vary from plus 21°C to minus 33°C from the mean. Torch igniters are used. Blades

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tested include zircon plus 2.5 per cent chromic oxide. A silicon carbide has been tested as blade material and found superior to zircon-chromic oxide. Blade cooling utilizes a two liquid system. The hollow blades are sealed with sodium potassium liquid metal. The test unit has been operated for twelve hours at maximum temperature without its rotor. Other development work includes flexible ducting, sprayers, fuel systems, air cooled combustion chambers, heat exchanger, materials, water cooled blades, turbine casings. A design of a 10,000 shp marine engine includes a maximum temperature of 1204°C and a specific fuel consumption of 0.39 lb. per shp-hr.

99-56 "Lightweight Mech-Hydro Locomotive for Train X"—Arnold B. Newell; Diesel Progress, August 1956, pp. 23-25. A new locomotive power package has been manufactured. It consists of a 1,000 hp diesel engine, hydraulic transmission, drive shaft and axle drives. The power package is so designed that it is easily removed and replaced. The transmission, Baldwin-Maybach, is fully automatic. It is comprised of a permanently filled hydraulic torque convertor, a four-speed gear box, including three pairs of helical gears operating together with overrunning clutches. There are four ahead speeds and reverse. The engine is a V-type, operating at 1,500 rpm, bore 7.3 in. and stroke 7.9 in. A spherical combustion chamber is located in the center of each cylinder head.

100-56 "The High Temperature Turbo-Jet Engine"—D. G. Ainley; The Journal of The Royal Aeronautical Society, V. 60, n. 549, Sept. 1956, pp. 563-589. High temperature operation and its related problems is discussed in relation to the future progress in turbo-jet engines. Greatest single problem is that of highly stressed blades in the turbine. Possible solutions include development of new material that could operate at higher temperatures or devising means of cooling existing materials. Thus gas temperatures could be raised while blade temperatures would remain at levels now found in existing engines. Methods of cooling blades include: liquid cooling where heat is absorbed by an expendable amount of liquid without reusing the liquid; combined liquid-air method where heat is removed from blades by a liquid which is then circulated and cooled in an air heat exchanger; air cooling where air is forced directly through inner portions of the turbine blades. These cooling methods are illustrated. Design and development of various types of cooled blades are presented. Basic requirements for efficient internal cooling, cooling characteristics of typical internally air-cooled blades, summary of practicability of air-cooling, choice of turbine design are discussed. Many problems are yet to be solved in blade cooling. At present an experimental air-cooled turbine at gas temperatures up to 1,400°C has been operated at

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N.G.T.E. A rise in engine temperatures of at least 150°-200°C should be expected. Discussions references, drawings, curves and photographs.

101-56 "Where Reactor Development Stands Today"—James A. Lane; Nucleonics, V. 14, n. 8, August 1956, pp. 30-37. Some 45 reactors are in use. These exclude units used for aircraft propulsion and Pu production. Estimates show about 172 reactors will be in use by 1960. Programs of the U.S., Russia and Britain are discussed. The U.S. power-reactor program is tabulated. Cost of power from nuclear sources and conventional methods, diesel and steam, compared. Feasibility studies of power reactors with various coolants and moderators are listed with estimated dates of established technical feasibility. References.

102-56 "25,000 Hours of Free Piston Engine Operation"—Gregory Flynn, Jr.; SAE Journal, V. 64, n. 10, Sept. 1956, pp. 64-70. The following free piston engines account for some 25,000 hours operation: Muntz P-42 air compressor; Sigma P-13 air compressor; GM-14 gasifier; GMR 4-4 (Hyprex) gasifier. Main problems include: cylinder wear; diesel piston ring wear, scuffing, and breakage; compressor piston ring wear, scuffing and breakage; intake valve failures; oil leakage past seals resulting in valve deposits and airbox fires; piston ring groove deposits; high piston cooling oil consumption. Considerable running time has been accumulated on bunker "C" fuel with the GM-14 gasifier. This engine showed great improvement over earlier free piston engines. After 4,500 hours at full load valve blades showed no evidence of fatigue failure. During this engine test no shutdowns were caused by injector seal leakage, precombustion chamber failures or intake valve failures. A 4,500 hr. test can now be run with more than 90% availability. The GM-14 engine will be a contender for commercial power generation.

103-56 "High Temperature Brazing"—Robert M. Evans; Battelle Technical Review, V. 5, n. 8, August 1956, pp. 8-12. Processes using filler metals that melt above 1,600°F. and techniques for joining assemblies to operate in temperatures above 1,000°F. are discussed. High temperature brazing has been used: to fix turbine blades of gas turbines to rotors; in manufacture of heat exchangers for high temperature corrosion-resistant service; for production of Diesel components and metal to ceramic seals. Applications where greater use of brazing may take place include: aircraft engine parts, fuel systems, sandwich structures, heat exchangers; missile fuel systems, precision parts, temperature controls, burner assemblies and exhaust chambers; mechanical power valves, piping, turbine blades, nozzles, preheaters, boilers; nuclear power heat exchangers, fuel elements, pressure systems and controls.

CAPTAIN HENRY C. DINGER, USN, Retired

Discussion of

Nuclear Power and the Navy, by Rear Admiral H. G. Rickover, USN, JASNE, February 1956

THE ARTICLE BY Admiral Rickover in the February 1956 number should be of the greatest interest to Naval engineers and as an example of the application of sound engineering to a problem from its conception to its successful completion.

Regarding the statement that Theodore Roosevelt caused the Navy to change from coal to oil, I am somewhat confused and am wondering upon what data this was based.

It happens that I was rather closely identified with this matter. It was not any definite change but a slow transition covering over twenty-five years. The first real beginning was the Navy Liquid Fuel Board. Extracts of this report were made in the J.A.S.N.E. 1904.

These tests were conducted at Washington, D.C. during 1902-1903 and burners were tested on boilers of a U.S. torpedo boat and on the Water Tube Hohenstein boiler lent by the manufacturer. These used steam, or air atomizers, none of which was later used or adopted for general Navy use. I personally helped in the preparation of the Fuel Oil Report for publication while on duty in the Bureau of Engineering in 1903. After publication of the report there was not much done by the Navy regarding oil for a number of years but there was activity in Europe. In my article, J.A.S.N.E. 1909, the situation was discussed. The British Navy developed the idea of supplemental burners where oil was burned above the coal fire on cross drum boilers and the White Company in conjunction with the Admiralty, I believe, developed the mechanical atomization burner. Other burners of this type were built by Yarrow, Thornycroft, Normand, and others and by Shuette-Korting in Germany and U.S. These were the burners used on the first U.S. oil burning destroyers commissioned in 1910. I had command of the *Drayton* with Normand boilers and burners.

In the meantime the scheme of supplemental oil burners was used on U.S. capital vessels going into service about 1910. About 1907 Capt. Norton, head of the Bureau of Steam Engineering design division was sent on a trip to Europe and brought back prints of the White Company, or Admiralty, burner which was then considered superior to the other proprietory burners. The bureau made detail drawings and designated Navy Yards Norfolk and New York to build burners and to test them out on a furnace test rig. I made such tests at Navy Yard Norfolk about May 1908. We gained knowledge of air control and also some on heating and oil pressure to use, position of burner and the relative efficiency of different air controls and sprayer tips. Anyway we discovered enough to report that burners of this type could be successful if installed on Naval boilers then in use. This was done; the first capital ships burning oil only were put into service about 1913. This is when the U.S. Navy really adopted oil fuel though coal continued to be used. The Navy fuel oil testing plant was started about this time at Philadelphia Navy Yard and there the Navy mechanical atomization fuel oil burners and system were developed and perfected. An important part of the activities of the station was the training of Naval and Merchant Marine oil firemen: an item fully as important as the mechanical perfection of the burner tips. The importance of this factor is emphatically brought out by Admiral Rickover. Whereas under his supervision by a fortunate combination of know-how with authority and a scientific analysis of the forces of nature, known and unknown, engineering and financial cooperation, the successful transition to a completely new power system was accomplished in a few years, coal to oil required half a lifetime. It is an almost complete answer to many of the questions raised by the article on logistics in the same number of the Journal (page 527).

BOOK REVIEWS AND NOTICES

ABACS OR NOMOGRAMS

By A. Giet
Translated and Revised by
J. W. Head and H. D. Phippen
Published in 1956 by
Philosophical Library, Inc.
15 East 40th Street, New York 16, N.Y.
225 pages $12.00

Most engineers have made use of nomograms at some time in their careers, and are fully alive to the fact that they are a very convenient tool when the same formula has to be solved repeatedly for several sets of variables. It is fair to say, however, that only a small proportion of even those who habitually employ nomograms know how to construct them for their own use. Most of the comparatively small literature on the subject is written for mathematicians and is extremely difficult for the practical engineer to comprehend. The present work, which is the translation of a book that has enjoyed considerable success in France, does not suffer from this defect. It is essentially practical, and not only demonstrates the many and varied applications of the abac or nomogram, but shows how even those without highly specialized mathematical knowledge may construct their own charts. It deals with both Cartesian abacs and alignment charts, and contains a large number of practical examples drawn from the fields of mechanics, physics and electrical engineering. Very few formulae are outside the scope of nomograms if skillfully chosen auxiliary variables are introduced.

This edition, which has been specially adapted for English readers, will prove of the greatest practical interest to engineers and physicists, and many others who require timesaving methods when performing repetitive and complicated calculations.

Chapter headings:

I—Relations Between Two Variables
II—Cartesian Abacs
III—Alignment Charts
IV—Alignment Charts Not Based on Parallel Coordinates
V—Relations Between n Variables ($n > 4$)

PRACTICAL SOLUTION OF TORSIONAL VIBRATION PROBLEMS

Volume I, Third Edition Revised
By W. Ker Wilson
Published in 1956 by
John Wiley Sons, Inc.
440 4th Avenue, New York 16, N.Y.
704 pages $16.00

Volume I covers frequency calculations and analyses of the characteristics of different types of oscillating systems, with examples from marine, electrical, aeronautical, and automobile engineering practice. Volume II (not included in this Book Notice) covers the calculation of torsional vibration amplitudes and stresses.

Because of the better understanding of the more complex aspects of torsional vibration that has occurred during the past ten years, this volume is completely rewritten to bring the subject matter up to date, while at the same time providing a comprehensive treatment in a form suitable for every day reference. In particular the sections dealing with geared

systems and systems containing distributed masses have been considerably expanded. Also the effective inertia method for determining natural frequencies is discussed in greater detail and a more comprehensive treatment is given to the application of this method in cases of coupled vibration.

Chapter headings:

I—Simple Systems
II—Frequency Tabulations
III—Multi-Mass Systems
IV—Simple Geared Systems
V—More Complicated Geared Systems
VI—Coupling Effects in Geared Systems
VII—Effective Inertia Method—Concentrated Mass Systems
VIII—Effective Inertia Method—Distributed Mass Systems
IX—Coupled Torsional and Flexural Vibration in Engine Systems
X—Equivalent Masses
XI—Equivalent Shafts
XII—Official Requirements Relating to Vibration

The JOURNAL of the American Society of Naval Engineers has recently reprinted two articles by the author of this book. "A Review of Ship Vibration Problems" was published in the May 1956 JOURNAL, and "The Noise Problem On Board Ship" was reprinted in the August 1956 JOURNAL.

THE GENERATION OF ELECTRICITY BY WINDPOWER

By E. W. Golding
Published in 1956 by
Philosophical Library, Inc.
15 East 40th Street, New York 16, N.Y.
318 pages $12.00

This is a very readable, thorough and interesting treatise on the harnessing of windpower covering historical, theoretical and practical aspects. It is sufficiently technical to make it of interest and of occasional value as a reference work to any engineer in the field of fluid mechanics or aerodynamics. It provides excellent examples of "off-beat" applications of such topics as momentum, Bernoulli's Law, effect of blade loading, laminar and turbulent flow, Magnus effect, power and energy relationships, aerodynamic experimental techniques, etc. Excellent material is included on the meteorological aspects of wind,—observation methods, recording methods, and the interpretation and explanation of observed behavior.

Especially noteworthy is the scope and completeness of the bibliographies. One is included with each chapter plus an Appendix bibliography listing available earth surface wind data.

SPECTROSCOPY AT RADIO AND MICROWAVE FREQUENCIES

by
D. J. E. Ingram
Published in 1956 by
Philosophical Library, Inc.
15 East 40th Street, New York 16, N.Y.
332 pages — Price $15.00

Microwave and radiofrequency spectroscopy has developed with great rapidity over the last ten years, and is finding an increasing number of applications in many fields of science. Research in the subject requires knowledge of physics and electronics of quite a high standard, but has now developed sufficiently for the publication of this general outline for those who wish to apply the techniques in their own field of study or to obtain a broad picture of its methods and applications.

Although approaching the subject in a general way, considerable space is given to the design of experimental apparatus for those who wish to set up such spectroscopes, and in considering the applications of the technique a balance is preserved between fundamental and applied research. The theory is given for each of the three main branches of the subject and although detailed mathematical treatment is avoided, this is illustrated at some length by reference to the various experimental results.

Captain

HERBERT NORTON PERHAM

USCG (Ret)

Captain Herbert Norton Perham, a U. S. Coast Guard engineer for 37½ years, and a veteran of World Wars I and II, was born on September 10, 1886, at Rutherford, New Jersey. He was graduated from Rutherford High School and the Webb Institute of Naval Architecture, New York City (class of 1907). Before finishing college he had made many trips to Europe serving in the Merchant Marine in various jobs on deck and in the engine department to study the operation of steamers.

From 1907 to 1909 he served under Admiral D. W. Taylor at the U.S. Naval Experimental Model Basin, Washington, D.C. During this period he journeyed to shipyards in England, Ireland, Scotland, Holland, Belgium and Germany to observe Naval construction practices.

In May 1909, having passed an examination for cadet engineer in the U.S. Revenue Cutter Service (forerunner of the U.S. Coast Guard) he was assigned to the Practice Cutter ITASCA and School of Instruction (as the early Coast Guard Academy was known before it was moved to New London, Conn. in 1910) at Arundel Cove, Md. He received his commission of Ensign (Engineering) on January 14, 1910.

By 1937 his duties as an engineer officer had included five practice cruises to the North of Europe, Baltic, Mediterranean, North Africa; one practice cruise to the Gulf and West Indies; eight Alaskan cruises including two seasons in the Alaskan Arctic with the famous Coast Guard Cutter BEAR; three Ice Patrol and Ice Observation cruises aboard the Cutter SENECA, service at the Honolulu station with the Destroyer Force and various other assignments on the Atlantic and Pacific coasts. During World War I he assisted in seizing and reconditioning the interned German ships at New York and served in the Construction and Repair division and as constructor officer at the Coast Guard Depot, Baltimore (presently known as the Yard), where was handled the overflow of work from the Norfolk Navy Yard.

He served as Chief of the Marine Engineering Section at Coast Guard Headquarters from September 1933 until June 1943. During this time he also served as Member of the Technical Advisory Committee to the Senate on Safety of Life at Sea and as Member of the Sub-Committee on Engineering, Fire Prevention, Detection and Extinction and Life Saving and Special Appliances, Board on Life Saving Appliances, Treasury Department Committee to the Federal Fire Council, and the Federal Interdepartmental Safety Council.

He was lastly assigned to the Engineering office of the 3rd District, New York, where he served until his retirement on November 1, 1946.

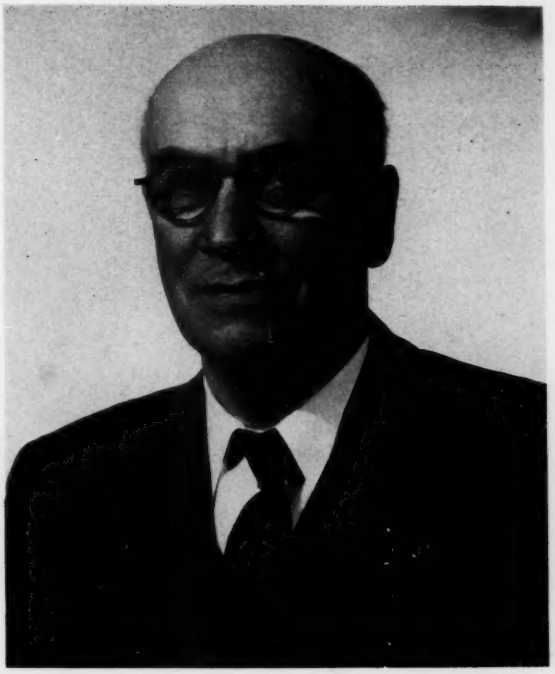
Captain Perham was promoted as follows during his service career: Ensign, January 14, 1910; Lieutenant (jg), August 7, 1914; Lieutenant, January 12, 1923; Lieut. Commander, July 1, 1926; Commander, April 23, 1930; Captain, December 1, 1940.

He was an active member of the Society of Naval Architects and Marine Engineers, the American Society of Naval Engineers, having joined in 1914 and remaining an active member until his death, The U. S. Naval Institute, the Institution of Naval Architects (London), and the Travel Club.

(In his spare time Captain Perham enjoyed a hobby of studying arms and armor, specializing in swords of which he believed he had one of the largest private collections in the country. These consisted of hundreds of different types of the 16th, 17th, and 18th century periods. Many of these he obtained during foreign cruises in the line of duty and while visiting foreign ports on leave. His collection also included hundreds of guns, pistols and revolvers which showed the evolution of firearms from the match lock of the Colonial Revolutionary period up to modern arms.)

Captain Perham died of a heart attack on September 4, 1956 at his home in Tacoma, Washington. He was buried in Arlington National Cemetery with full military honors at 2 p.m., September 12. Survivors are his wife, Mrs. Helen Hoit Perham and daughter, Mrs. Betty M. Amos, wife of Captain Marion Amos, USCG.

MR. KARL D. WILLIAMS



On September 4, 1956, death took one of the Society's most prominent members, Mr. Karl O. Williams, Honorary Member.

The Society elected Mr. Williams to honorary membership in the 1956 election, with the following citation:

"In view of his outstanding contributions in the field of metallurgy; for the great resourcefulness, initiative and ability which he exercised in bringing about fulfillment of many programs of highest importance to the Navy; for his counsel to many Naval Engineers and young officers with whom he has worked and for his good citizenship, the American Society of Naval Engineers takes great pleasure in designating Karl Dayton Williams, an Honorable Member of The Society."

Mr. Williams' health prevented his attendance at the 1956 banquet where other awards were made. His citation was read on that occasion by past-president and former close associate of "K. D.", Rear Admiral Roger W. Paine, USN, Ret. The Secretary-Treasurer had the privilege of presenting the certificate of honorary membership to Mr. Williams at his home as noted in the August 1956 issue of the Journal.

K. D. received many other citations for his many valuable contributions particularly in the field of metallurgy. He began his career in the Bureau of Steam Engineering in the Navy Department in 1917, retiring in 1949. During this period, the Bureau and its successor bureaus came of age, metallurgically speaking, largely under Mr. Williams' guidance.

During his later years with the Bureau of Ships, he was on the International Screw Thread Committee to standardize screw fittings and parts among manufacturers of allied nations, so that allied ships could readily obtain repairs in any friendly port in time of war.

Those who knew K. D. will remember him for his tact and patience and tenacity in sticking to problems in his field until solutions were found.

During his 37 years of membership in the Society, Mr. Williams contributed several valuable articles to the Journal.

He is, and will be, missed.

We are indeed grieved because of the necessity of reporting receipt of notice of the death of the following since the publication of the August Journal.

Caplan, Louis R., Civil Member
Wilson, L. F., Naval Member

ADDITIONS TO MEMBERSHIP

The Society announces with much pleasure that the following have been added to its ranks since the publication of the August, 1956, JOURNAL.

NAVAL

Bagni, Allan Gerald, Lieut., USNR
21 Nelson St., Plymouth, Mass.

Currier, Richard A., Lieut. (jg) USN
USS *Grampus* (SS 523)
c/o Fleet P.O., New York, N.Y.

Donnelly, Richard A. Jr., Lieut., USCG
107 Monadnoc Rd., Chestnut Hill 67, Mass.

Dunn, Arthur Elmer, Lieut., USNR
Radio Corp. of America
1625 K St., N.W., Washington, D.C.

Eidson, George Valentine, Lieut., USN
USS *Lowe* (DER 325)
Fleet P.O., San Francisco, Calif.

Fravel, Harold Albert, Comdr. USN (Ret.)
Asst. Prof. Mech. Engrg. George Washington University
Mail: 3410 15th St., North, Arlington 1, Va.

Giorgis, Albert Steve, Lieut. Comdr., USN
7201 Giles Place, Springfield, Va.

Hough, Donald W., Lieut., USNR
Asst. Direc. Experimental Test Div.
Reed Research Inc.
Mail: 1129 Patrick Henry Drive, Falls Church, Va.

Latham, William Bernet, Lieut. (jg), USN
USS *Warrington* (DD-843)
Fleet P.O., New York, N.Y.

Leete, Billie Jack, Lieut., USNR
Marine Engineer, Farrell Lines, Inc.
Mail: 610 E. Hereford St., Gladstone, Ore.

Lloyd, James Lott, Lieut., USN
USS *Menhaden* (SS 377)
Fleet P.O., San Francisco, Calif.

Lonnquest, Theodore Clayton, Jr., Lieut., USN
Naval Ship Installation, Test Facility
NAS, Lakehurst, N.J.

McFann, Howard Leslie, Lieut., USNR-R
782nd AC & W Squadron, Rockville, Ind.

Mitchell, Robert Paul, Lieut. Comdr., USN
Resident Supervisor of Shipbuilding USN & NIO
c/o American Shipbuilding Co.
Foot of W. 45th St., Cleveland 2, Ohio

Muller, James D., Lieut., USN
USS *Union* (AKA-106)
Mail: 105-10 66th Ave., Forest Hills, New York, N.Y.

Organ, William, Rear Admiral, USN (Ret.)
Federal Telecommunication Laboratories
500 Washington Ave., Nutley 10, N.J.

Robinson, Stanley James, Comdr., USN (Ret.)
Andale Company
1740 Chenny St., Philadelphia 3, Pa.

Scharfenstein, Charles Frederick, Jr., Comdr., USCG
618 Second Ave., Seattle 4, Wash.

Solomon, Herbert D., Lieut. Comdr., USNR
MSTS Westpac Area
c/o Fleet P.O., San Francisco, Calif.

Thornbury, Joe Warren, Lieut. Comdr., USN
Naval Administrative Unit, MIT, Cambridge, Mass.

Warren, Richard L., Lieut. Comdr., USN
U. S. Naval Schools Command
Officers' Candidate School, Newport, R.I.

CIVIL

Bittner, Howard Bernard, Asst. Govt. Sales Mgr.
Automatic Electric Sales Corp.
1033 W. Van Buren St., Chicago 7, Ill.

Corbin, Henry Clark, Sales Engineer
Vapor Heating Corp.
517 E. Illinois Rd., Lake Forest, Ill.

Curry, George U., Asst. Chief Engineer
Henschel Corp., 14 Cedar St., Amesbury, Mass.

Hart, Frank A., Sales Engineer, C. H. Wheeler Mfg. Co.
Mail: Rhinebeck, N.Y.

Hofstetter, John M., Marine Application Engineer
I.T.E. Circuit Breaker Co.
19th and Hamilton Sts., Philadelphia 30, Pa.

Jasper, Norman Hans, Head Appl. Dynamics Branch
David Taylor Model Basin
Mail: 6331 Tone Drive, Bethesda 14, Md.

Stewart, Curtis C., Publisher National Hi-Way Shipper
343 So. Dearborn St., Chicago 4, Ill.

Tichaz, Bernard, Project Engr., Geo. G. Sharp, Inc.
Mail: 58 Elm St., Maplewood, N.J.

CHANGES IN MEMBERSHIP

ASSOCIATE

Brooks, Leon O., U.S.A. Engrg. Rep. of D. Napier & Son, London, England
Mail: Needwood Farm, Derwood, Md.

Cirbee, Henry A., Sales Engr., Reliance Elect. & Engrg. Co.
Mail: 1025 Connecticut Ave., Suite 811, Washington, D.C.

Gingras, Louis Dona, Prof. Engr. General Elect. Co.
Mail: 117 Scarborough Rd., Pawtucket, R.I.

Shepherd, Maxwell Robert, Chief Quarterman Unit III
Shop 38 (Marine Machinist)
Subic Bay, Philippine Islands
Mail: Navy 3002, Box 34
Fleet P.O., San Francisco, Calif.

REJOINED

Brown, T. T., Naval Member

TRANSFERRED JUNIOR TO NAVAL

Wildman, James R.

RESIGNED

Dampman, John L., Junior Member
Flint, Morris B., Naval Member
Kaplan, Robert T., Civil Member
Kouvenhoven, A. B., Associate Member
Lanthorn, Elmer Holzer, Naval Member
Pettigrew, Richard Ross, Naval Member
Smith, John R., Associate Member

ASSOCIATION NOTES

ORIGINAL ARTICLES

The editor of the JOURNAL is most anxious to obtain manuscripts of original articles on subjects of interest to naval engineers. Any manuscript accepted for publication becomes the property of the Society which copyrights it upon publication. Authors are paid from $50.00 to $250.00 depending upon length, interest and professional value. Payment is made at time of acceptance.

The rules for manuscripts are as simple as we can make them.

1. They must be legible (typewritten, double-spaced preferred) since no proof is submitted to authors for correction prior to printing.

2. Single copy only is required.

3. Mathematical formulae used must be set up, preferably by hand printing, so that there can be no question as to symbols, subscripts and exponents.

4. Any drawing submitted must be black on white. A cloth or paper tracing is acceptable but not required.

5 Photographs may be negatives, but glossy prints are acceptable.

6. *Include on a separate page a short biographical sketch(es) of the author(s).* 50 to 100 words for each author is desired.

Manuscripts should be addressed to:

Secretary-Treasurer
American Society of Naval Engineers, Inc.
1012 14th St., N.W.
Washington 4, D.C.

Each author who is subject to the Security Regulations of the Department of Defense, is personally responsible for the clearance of an original article before submitting it to the Society for consideration. In forwarding manuscripts, a statement in this regard should be included.

Manuscripts accepted will not be returned unless specifically requested by the author. If returned, they will be in the condition which has resulted from the work of the printer and the engraver. Immediately following publication, the author is furnished 20 reprint copies of his article free of charge. Additional copies may be purchased from the Society *if the request is received 30 days prior to the publication date which is the 25th of the issue month.* Estimate of cost of additional reprints, which will vary with the nature of the article and the number of copies ordered, will be furnished on request as soon as possible after the article is set up.

Manuscripts not accepted will be returned, postpaid, by the Society.

Manuscripts which are accepted will be published in the earliest JOURNAL which has not yet been closed (60 days before publication) and for which sufficient material is not already on hand.

ASSOCIATION NOTES

PHOTOGRAPHS

Photographs of current or historical interest to readers of the JOURNAL are desired. Any which are accepted by the Society will be purchased by the Society at a standard price of $5.00 each. Such purchase *will not* include any copyright by the Society, but the contributor must hold the Society free from any charge of violation of any previous copyright.

NOTICE OF DEATHS

The Society has no satisfactory machinery for obtaining notice of deaths of members. It is particularly desired that we receive such notice upon the death of any past officer, past member of the Council or member of more than twenty years' standing with photographs and short obituaries. It will be appreciated greatly if any member who learns of the death of a member will advise the Secretary-Treasurer.

SOCIETY LAPEL BUTTONS

We have a new supply of lapel buttons, in the form of the Society's official seal. These may be purchased by any member for fifty cents ($0.50) each.

By decision of the Council the official coloring of the Society seal is as it appears on the cover of this Journal. This is a reversal of the colors on the old lapel buttons. The size, one-half inch in diameter, remains the same.

Any member who wishes to exchange an old button for a new one may do so *free of charge*. Just send in the old button with your name and address.

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(See reverse side for required qualifications for various classes of membership)

Date _____

I, _____ hereby apply for membership in the American Society of Naval Engineers, Inc., and enclose $7.50 as my annual membership dues for the year _____ $6.00 of which is for a subscription to the JOURNAL OF THE AMERICAN SOCIETY OF NAVAL ENGINEERS, INC., for one year. I submit the following information:

For Naval Membership

Name _____
(First) (Middle) (Last)

Rank _____ File No. _____

Business connection and position, if any _____

For Civil Membership

Name _____
(First) (Middle) (Last)

Years in engineering work _____

Years in responsible charge of important work _____

Present business connection and position _____

Recommended by (two members) _____

_____

For Associate Membership

Name _____
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Rank, if Commissioned Officer of U.S. Army

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Business connection and position _____

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1012 14th St., N.W.
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Commissioned and ex-commissioned officers of the regular Navy, Marine Corps and Coast Guard of the United States; warrant and ex-warrant officers of the regular Navy, Coast Guard and Marine Corps of the United States; reserve commissioned and warrant officers of the Navy, Coast Guard and Marine Corps of the United States shall be eligible as Naval Members. Persons eligible as naval members shall be admitted upon application and payment of annual dues.

Persons in civil life whose knowledge of engineering is such that they can cooperate with Naval engineers in the promotion of professional knowledge may be eligible as civil members. They shall have been in active practice of an engineering profession for at least eight years and in responsible charge of important work for five years, and shall be qualified to design as well as to direct engineering work. Fulfilling the duties of a professor of engineering who is in charge of a department in a college or school of accepted standing shall be taken as an equivalent to an equal number of years of active practice. Graduation from a school of engineering of recognized standing shall be considered as equivalent to two years of active practice. Persons eligible as civil members may be admitted upon application and payment of annual dues, provided that the application is accompanied by the recommendation of two members and provided that the application shall receive the approval of a majority of the Council.

Persons in civil life who are not eligible for civil membership, but who are especially interested in naval matters or the merchant marine may be eligible as associate members. Commissioned officers of the United States Army and of foreign military and naval services may be eligible as associate members. Persons eligible to associate membership may be admitted upon application and payment of annual dues, provided the application have the recommendation of a member and provided the application shall receive the approval of a majority of the Council, except that in the case of commissioned officers of the United States Army and of foreign naval and military services, the recommendation of a member will not be required.

Associate members shall be entitled to all the privileges of other members except voting and holding office.

The annual dues shall be $7.50, payable on 1 January in advance, of which $6.00 shall be for subscription to the JOURNAL of the American Society of Naval Engineers, Inc., for one year.

XU

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AMERICAN SOCIETY OF NAVAL ENGINEERS, INC.

Captain J. E. Hamilton, U. S. Navy Retired, Secretary-Treasurer

Captain Robert B. Madden, U. S. N. Assistant Secretary-Treasurer

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1909-10 **Lieutenant H. C. Dinger, U. S. Navy**

1911 *Commander U. T. Holmes, U. S. Navy*

1912 { *Lieutenant John Halligan, U. S. Navy*
Lt. Comdr. E. L. Bennett, U. S. Navy

1913 **Lieutenant O. L. Cox, U. S. Navy**

1914 **Lt. Comdr. H. C. Dinger, U. S. Navy**

1915-16 *Lieutenant A. T. Church, U. S. Navy*

1917 { **Lt. Comdr. J. O. Richardson, U. S. Navy**
Lt. Comdr. F. W. Sterling, U. S. Navy

1918 *Lt. Comdr. F. W. Sterling, U. S. Navy*

1919 { *Lt. Comdr. F. W. Sterling, U. S. Navy*
Commander J. S. Evans, U. S. Navy

1920 **Commander J. S. Evans, U. S. Navy**

1921 { **Commander J. S. Evans, U. S. Navy**
Commander S. M. Robinson, U. S. Navy

1922-23 **Commander S. M. Robinson, U. S. Navy**

1924-25 **Commander Bryson Bruce, U. S. Navy**

1926 **Commander A. M. Charlton, U. S. Navy**

1927 **Commander H. B. Hird, U. S. Navy**

1928 { **Commander H. B. Hird, U. S. Navy**
Captain O. L. Cox, U. S. Navy

1929-30 *Commander H. T. Smith, U. S. Navy*

1931 **Captain O. L. Cox, U. S. Navy**

1932 **Commander H. F. D. Davis, U. S. Navy**

1933-34 **Commander H. B. Hird, U. S. Navy**

1935 **Commander C. S. Gillette, U. S. Navy**

1936 { **Commander C. S. Gillette, U. S. Navy**
Commander Roger W. Paine, U. S. Navy

1937 **Commander Roger W. Paine, U. S. Navy**

1938 { **Commander Roger W. Paine, U. S. Navy**
Lt. Comdr. Guy Chadwick, U. S. Navy

1939-40 **Lt. Comdr. Guy Chadwick, U. S. Navy**

1940-44 **Captain J. E. Hamilton, U. S. Navy**

1945 **Commander R. T. Sutherland, Jr., U. S. Navy**

1945-48 **Captain F. W. Walton, U. S. Navy**

1948-51 **Captain J. E. Hamilton, U. S. Navy**

Past Assistant Secretaries

1939-40 **Lieutenant Milo B. Williams (C.C.) U. S. Navy**

1941-44 **Lieutenant Robert T. Sutherland, U. S. Navy**

1944 **Captain F. W. Walton, U. S. Navy**

1944-47 **Commander Floyd B. Shultz, U. S. Navy**

1947-49 **Commander C. H. Meigs, U. S. Navy**

1949-50 **Commander Frank C. Jones, U. S. Navy**

Clerk and Administrative Assistant

1908- **Mr. Arthur G. Fessenden**

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*Names in italics deceased